CAIO DE CARVALHO LUCARELLI

INVESTIGATION OF A PERFORMANCE-BASED PARAMETRIC CANOPY

Dissertação apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Arquitetura e Urbanismo, para obtenção do título de *Magister Scientiae*.

Orientadora: Joyce Correna Carlo

Coorientadora: Andressa Carmo Pena Martínez

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To my Family Hêliandra, Helvécio,
Evelize, Nicole, Miguel Mel and Liz.
In Memorian of Paçoca.

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"We must try not to sink beneath our anguish … but battle on."

(Rowling, J. K.)

ABSTRACT

LUCARELLI, Caio de Carvalho, M.Sc., Universidade Federal de Viçosa, February, 2020. **Investigation of a performance-based parametric canopy.** Advisor: Joyce Correna Carlo. Co-advisor: Andressa Carmo Pena Martínez.

In recent years, global energy demand has increased substantially due to population growth. Therefore, improvements in energy efficiency have become a prominent international business for designers and researchers. This need to create environmentally sustainable projects with lower impact, better thermal comfort, and reduced energy consumption has encouraged the spread of one of the 21st-century design streams called performance-based design. For this reason, this dissertation aims to investigate the steps of creating a performance-based modular canopy, fitted for allowing diffuse radiation and daylight indoors using parametric modeling, simulation-based optimization (SBO), and factorial analysis. We used canopies as objects of study due to the higher insolation load that horizontal surfaces receive in low latitudes, which is Brazil's case. We divided the research into a literature review, a methodology testing, digital shape production processes, shape definition, shape parameterization, computational simulations, the definition of SBO parameters and objectives, and final shape optimization. We introduce the study with a methodology test, formulating a script, running simulations for radiation, and using SBO to produce a canopy based in retro-studies of tree leaves as engineering structures. With the methodology tested, we proceed to the parameterization of the definitive shape, using an analysis of variance (ANOVA) to determine the most robust optimization parameters that would partake in the final SBO. We apply the awning to several naturally conditioned transitional spaces. These transitional spaces present neither indoor nor outdoor conditions and have historical value in Brazil, being present in architecture since the colonial period. They act as passive design strategies, improving the results obtained when simulation the canopy alone. In this study, the transitional spaces are an Entrance Hall, a Fan Atrium Zone, and a Balcony. As the main result, we obtained a process for designing both a leave inspired canopy and an Origami-shaped awning. We presented a methodology for applying SBO during early design stages using Ladybug® and Honeybee® for Grasshopper®. We also diminished the optimization time by selecting the robust optimization parameters beforehand using ANOVA. Concluding, the parameterization and SBO employed analysis concerning radiation and daylight through the assessment of the quantitative objectives Physiological Equivalent Temperature (PET) and Useful Daylight Illuminance (UDI).

Keywords: Complex Surfaces. Parameterization. Simulation based Optimization. Luminous and thermal performance.

tempo de otimização, selecionando previamente os parâmetros robustos de otimização usando ANOVA. Concluindo, a parametrização e a SBO empregaram análises de radiação e luz natural por meio da avaliação dos objetivos quantitativos Physiological Equivalent Temperature (PET) and Useful Daylight Illuminance (UDI).

Palavras-chave: Superfícies Complexas. Parametrização. Otimização baseada em Simulação. Desempenho térmico e luminoso.

RESUMO

LUCARELLI, Caio de Carvalho, M.Sc., Universidade Federal de Viçosa, fevereiro de 2020. **Desenvolvimento de uma cobertura paramétrica baseada no desempenho.** Orientadora: Joyce Correna Carlo. Coorientadora: Andressa Carmo Pena Martínez.

Nos últimos anos, a demanda global de energia aumentou substancialmente devido ao crescimento populacional. Portanto, melhorias na eficiência energética se tornaram um negócio internacional de destaque para ‘designers’ e pesquisadores. A necessidade de criar projetos ambientalmente sustentáveis com menor impacto, melhor conforto térmico e menor consumo de energia incentivou a expansão de uma das correntes de ‘design’ do século XXI: o ‘design’ baseado em desempenho. Por esse motivo, esta dissertação tem como objetivo investigar as etapas do processo de criação de uma cobertura modular baseada em desempenho, capaz de permitir radiação difusa e luz natural em ambientes internos usando modelagem paramétrica, otimização baseada em simulação (SBO) e análise fatorial. Usamos coberturas como objeto de estudo devido à maior carga de radiação que as superfícies horizontais recebem em baixas latitudes, como é o caso do Brasil. Dividimos a pesquisa em revisão de literatura, teste de metodologia, processos de produção de geometrias digitais, definição da geometria, parametrização da forma selecionada, simulações computacionais, definição de parâmetros e objetivos do SBO e otimização da forma. Introduzimos o estudo com um teste de metodologia, formulando um 'script' em Grasshopper, executando simulações computacionais para radiação e usando o SBO para produzir uma cobertura baseada em retro estudos de formas da natureza como estruturas de engenharia. Com a metodologia testada, procedemos à parametrização da forma definitiva, usando uma análise de variância (ANOVA) para determinar os parâmetros de otimização mais robustos para a SBO final. Aplicamos a cobertura em vários espaços de transição naturalmente condicionados. Esses espaços de transição não apresentam apenas condições internas nem externas de conforto e têm valor histórico no Brasil, estando presentes na arquitetura desde o período colonial. Eles atuam como estratégias de projeto passivo, melhorando os resultados obtidos ao simular apenas a cobertura. Neste estudo, os espaços de transição são um Vestíbulo, uma Zona de Átrio e uma Varanda. Como resultado principal, obtivemos um processo para projetar coberturas inspiradas por formas da natureza e por formas do Origami. Apresentamos uma metodologia para aplicar o SBO durante os estágios iniciais do projeto, usando Ladybug® e Honeybee® for Grasshopper®. Também reduzimos o

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SUMMARY

1 CHAPTER 1 – OVERALL INTRODUCTION

1.1 Introduction

The energy-efficient building tendency has been established for more than three decades among government, developers, and architects. Recently, it was backed by an awareness of climate change and other environmental hurdles, such as industrial development, the growth rate of the world population, the increasing of social welfare, and a surge in the global demand for energy. (SHI, XING et al., 2016)

In this regard, the building sector is the largest energy consumer amongst all sectors. It accounts for about 37% of the total energy for cooling, heating, and lighting in the USA, and 36% of the carbon dioxide emission of developed countries (EVINS, 2013; SHI et al., 2016). Despite this, this is the sector with the greatest potential and lowest cost for carbon reductions. (DELGARM et al., 2016)

According to Kirimtat et al. (2019), a struggle toward reaching high-energy performance and carbon reduction is in the design process. The early stages of the building design are marked by multidisciplinary and conflicting objectives in which the first design decisions impact on building performance. (ECHENAGUCIA et al., 2015; ELBELTAGI et al., 2017)

For Touloupaki and Theodosiou (2017), the evaluation of energy performance in an early design stage, even though demanding, should be considered, as it offers a range of opportunities for integrating passive strategies. This integration can be analog or digitally connected to local climate factors through computational simulations.

According to Umakoshi (2014), computational simulations are employed during three stages of the design process. When they are applied in the conception stage, they have a generative contribution. During the design process, they allow testing ideas or solutions. If applied at the end of the process, they serve as performance evaluation simulations. For Gokmen (2013) and Oxman (2006), when they are used during the design process or later, they are limited to predetermined shapes and established components, which creates a gap between design and simulation.

If combined with shape generation processes from the beginning, this gap ceases to exist, creating a building geometry based on its performance. (UMAKOSHI, 2014)

According to Hitchcock (1995), computational simulation covers any term related to algorithms that mimic the physical process of designing. It can be used for the prognostication and maintenance of buildings and, even twenty years ago, it was already unanimous in the design area (MENDES; LAMBERTS; NETO, 2001). Since the 1990s, computational simulation has been combined with optimization for handling complex engineering systems. Nowadays, this combination is still a promising method broadly applied.

Building performance optimization can be implemented in various stages of design, planning, and construction. According to Fang (2017), with the progression of computational technology, there are numerous tools available to assess building performance.

According to Shi and Yang (2013), the “performance-driven […] design emphasizes on integrated and comprehensive optimization of various quantifiable performances of buildings” (SHI; YANG, 2013, pp. 125). It conveys a holistic view of ecological and environmental performances[1] while ensuring that the use and aesthetic are not overlooked.

The worth of programming for problem-solving in architecture, engineering, construction, and operations (AECO) has been well-known since the 1960s. Nevertheless, its applications on the architectural design process are more frequent from 1990 onwards. (NATIVIDADE, 2011)

The performance-driven design has a more effective approach to efficiency and to process steps interoperability. It is a strategy for developing buildings that meet a specific objective with the best results. Optimizing “is often referred to [as] the procedure […] of making something (as a design, system, or decision) as fully perfect, functional, or effective as possible.” (NGUYEN et al., 2014, pp. 1044)

Regarding architecture, energy-efficient design optimization relies on optimization algorithms to generate new forms based on simulation results and user-defined design objectives.

According to Evins (2013), evolutionary algorithms are among the most commonly applied in optimization. They are based on the Darwinian principle of survival of the fittest, eliminating the poorest in every generation.

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[1] For Shi and Yang (2013), these are indicators that enable to measure the impacts of industrial activities and buildings, since the performance of new buildings affects the overall quality of urbanization.

They are classified into two categories: the conventional gradient-based and the gradient-free search. The gradient-free search or global optimization strategy is the fittest for building applications. It can deal with irregular variables and multi-modal problems, finding an acceptable or near-optimal solution using less computing time in comparison to other algorithms. (NGUYEN et al., 2014)

Integrating energy-efficient and performance-driven design into architecture practice is challenging. Most simulation tools require a substantial amount of work and time to achieve accurate results. Sometimes, it is necessary to use different software to achieve the expected output. However, once you get the optimal combination of tools,

> […] simulations can be performed automatically and the results stored and organized according to their performance. Thus, rather than setting changes for each simulation, users can set a design problem, and then, obtain the solution […] for that problem. (GONZÁLEZ; FIORITO, 2015, pp. 562-563)

This is the premise of parameterization, which was resignified into digital shape modeling as a process of automation of the design, being introduced to the performance simulation over the last three decades.

Different from its definition in computer science, “parametric design, in architecture, refers to the modeling process of building geometry using parameters and functions” (FANG, 2017, pp.3). Its benefit is in the possibility of generating new design alternatives swiftly, through the manipulation of parameters.

According to Woodbury et al. (2011), parametric modeling allows designers to model aspects of design and parts of the editing process so that they can create both their work and how it can change its context.

It is common during the creative design process that specific building features are revised or modified several times. To simplify this process, an arrangement built into computer programs, based on parameters and hierarchies, was developed: the parametric variations. Thus, parametric modeling of the geometry has enabled the advancement of complex designs with the creation of rules and relationships between elements. According to Campos and Celani (2017),

> Parameterization alone is capable of providing complex solutions, but in order for it to address [issues] such as structure, lighting, thermal performance and others, it is also necessary to use computer simulations. Using both tools, combined with optimization methods (either by [optimization] algorithms or others), it is possible to create solutions that correspond to better building performance in certain aspects that are important for that work, allowing a better extensive exploration in the design process, which goes beyond the

> generative dynamic capability of parameterization. (CAMPOS; CELANI, 2017, pp. 20, our translation)

Some other issues related to AECO, such as connections, materials, and constructive envelopes are also a concern of parameterization. By organizing an architectural solution logically, this method can be applied to various components in a process of architectural automation.

Concerning multidisciplinary design, the constructive envelope is one of the most studied parameterization objectives (CARTANA, 2018; KIRIMTAT et al., 2019) since it significantly influences energy efficiency, daylight admission, and indoor environmental quality. (CARTANA, R. P.; PEREIRA; MAYER, 2018; ECHENAGUCIA et al., 2015)

According to Samuel, Akwara and Richard (2017), the constructive envelope is the most critical factor influencing energy performance. Several studies have shown that its thermal properties have a major impact on the proportion of operational energy required by the buildings, especially for cooling and heating systems (CHAN; CHOW, 2014; NOORI; HWAISH, 2015; SADINENI; MADALA; BOEHM, 2011). Various studies report the use of performance-driven design, optimization, and design-support algorithms in the building and construction sector applied to the built envelope optimization (HUANG et al., 2014; KARMELLOS; KIPRAKIS; MAVROTAS, 2015; PENNA et al., 2015). According to Fajkus (2013), the energy performance assessment of these systems has become increasingly important in contemporary architectural production.

In consonance with Kirimtat et al. (2019), overheating is a major obstacle to regulations in hot climate regions. It leads to an excessive amount of energy consumption because of the higher operation time of active systems. Passive strategies are cost-efficient solutions fit for dealing with the overheating problem.

“As an instance of prominent passive systems, the shading devices are the components mounted on the building envelopes to improve energy efficiency by preserving renewable resources” (KIRIMTAT et al., 2019, pp. 101). They protect the interior from overheating while providing sufficient daylight and can be incorporated in the building envelope in the form of double skin facades, louvers, light shelves, canopies, and others.

Dealing with the challenge of designing a shading device for a building envelope demands performance evaluation based on optimization methods due to many conflicting objectives (KHOROSHILTSEVA; SLANZI; POLI, 2016). Most studies concentrate on presenting alternative solutions for designing shading geometries focusing on performance evaluation using optimization and simulation techniques. (KIRIMTAT et al., 2016; LI; QU; PENG, 2016; PESENTI; MASERA; FIORITO, 2015; YU, W. et al., 2014)

According to Pesenti, Masera, and Fiorito (2015), this happens because shading devices and building envelopes are composed of many layers that enable the construction to operate accordingly. Because of their complexity of materials and morphology, sometimes they maintain a close relationship with information technologies, outfitting a concept of complex surfaces[2]. (PAOLETTI, 2006)

Concerning the geometry of these envelopes, Pesenti, Masera, and Fiorito (2015) have drawn attention to the potential of Origami's creased patterns, reviewing how their shapes can be modeled to optimize their surface displacements.

“Origami is the art of folding or [...] isometrically transforming a sheet of paper into various forms without stretching, cutting, or gluing another piece of paper to it” (TACHI, 2010, pp. 203). It creates a complex design that can be applied to several architecture elements without the need for assembly.

A reason for choosing Origami as a process for producing a shading device is the spontaneous self-organization of these particular geometries. Thanks to the weaving creases, the pleats allow the system to deform in a predefined direction, remaining rigid in the others. Other investigations also show that these arrangements can change their shape to accommodate new conditions while preserving a continuous outer surface. (PERAZA-HERNANDEZ et al., 2014)

Concerning building envelopes, in low latitude countries such as Brazil, canopies account for large heat gains. Nevertheless, the researched literature is comprised of façade studies simulated in higher latitudes.

Since passive strategies are considered a cost-effective and straightforward approach to achieving improved energy performance, the situation chosen for the canopy simulation is a transitional space. According to Pitts (2013), they can be balconies, foyers, lift lobbies, corridors, staircases within a building etc.

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[2] Complex surfaces are those that appear as fluid, shaped by spherical solids to form curved volumes, normally using information technologies to organize the construction process or other responsibilities and competencies. (PAOLETTI, 2006)

These spaces have historical value in Brazil besides acting as passive design tactics. The balcony, for instance, is a typical transitional space and has been present in architecture since the colonial period. (DAVID; RIOLI; FONTES, 2014)

Their application increases the building's energy efficiency and user comfort. They provide thermal, acoustic, and visual comfort, acting as a shading device, enabling adequate lighting and ventilation. They also protect the construction from direct sunlight, wind, and rain, aiding in conservation, extending its lifespan, and lessening the need for artificial lighting and conditioning solutions. (DAVID; RIOLI; FONTES, 2014)

Besides, these types of spaces have a strong social function. They are considered an extension of the inner/outer barrier. They act as a place for social interactions and are accessible to users of both, indoors and outdoors, intermediating and accommodating various activities. (UNWIN, 2010)

As users do not expect to find cooler temperatures in these locations, heat control is unnecessary, diminishing energy costs with air conditioning. Further, users are aware that this is typically a walk-in location used for gatherings and departures. So, the microclimate is considered comfortable even at higher temperatures.

Answering all the perceptions aforementioned, this research strives to elucidate the following question: How is the process of designing a performance-based canopy, created by simulation-based optimization?

1.2 Objectives

1.2.1 General Objective

The main purpose of this thesis is to investigate the performance-based design process for a canopy produced using shape parameterization, computational simulations, and optimization procedures.

1.2.2 Specific Objectives

I. Explore the process of designing and assessing complex architectural surfaces through parametric modeling, from a theoretical perspective to computational simulation for radiation as a methodology test;

II. Evaluate the preprocess of devising of a modular canopy based on Origami shapes according to solar geometry, through computational simulation, radiation optimization, and statistical analysis;
III. Implement the developed design and simulation processes to an Origami-inspired canopy employed on transitional spaces, examining performance indicators;

1.3 Methods

This research is of quantitative and exploratory type (GROAT; WANG, 2013), inserted in the area of Performance-Based Design, comprising factorial analysis and simulation-based optimizations for radiation and daylighting.

To explore a design process based on optimization methods, we use methodologies extracted from the literature review and architectural examples, following the subsequent methodological steps:

1.3.1 Summary of Methods adopted in Chapter 2

In the second chapter, we aim to analyze the process of designing using optimization strategies. For instance, Pesenti, Masera, and Fiorito (2015)and González and Fiorito's (2015) methodologies are incorporated into this dissertation because of their resemblance to the study of complex surfaces. Thus, we divided the research into three stages.

The first stage concerns the exploration and definition of geometry. It is a critical stage since the design needs a simplified approach to be replicated, given the complexity already associated with parametric geometries. Origami pleating and biomorphic shapes are contemplated since their kinematics surpasses the diversity permitted by Euclidean geometries.

For this chapter, as a methodology test, we used patterns found in nature. The starting point is an abstraction of leaves, because of their ability to behave hastily while creating protection from the weather.

The second stage contemplates the parameterization of the canopy. One of the premises of this investigation is to offer the possibility of implanting the canopy in different latitudes without design rework, changing only the weather file. The purpose of the script is to allow the alteration of small parameters to generate an optimized form.

The third stage concerns the simulation for radiation and shape optimization using Ladybug® and Octopus® for Grasshopper®. This part of the methodology, which combines Octopus® with a performance evaluation plugin, ensures high levels of environmental performance while reducing the time needed for extensive trial and error processes.

1.3.2 Summary of Methods adopted in Chapter 3

The goal of chapter three is to evaluate the parametric design process of an Origami shaped canopy fitted for permitting the admission of solar radiation indoors.

After a careful literature review on Origami pleating applied to architecture, we divide the methodology into four parts.

The first section regards the pleating selection. Acknowledging the research on Origami tessellations, the application of the Miura Ori form shows freestanding properties, rigidity, and easy mobility. For these reasons, we chose it for the assembling of the parametric script.

The second stage concerns shape parameterization. Using the Rhino3D® and Grasshopper®, a solar protection component is created based on the Miura-Ori buckling. We strive to explore the potential of the modeling tools and the behavior of complex surfaces employed as shading devices.

The third stage regards the utilization of a factorial analysis to ascertain the most sensitive geometry parameters for later optimization. We employ radiation simulation outputs as inputs for the factorial analysis and treat the results with an analysis of variance (ANOVA).

The fourth stage concerns the simulation of the canopy to question the variables in the factorial analysis. We extract the radiation analysis, Operative Temperature (To), and Percentage of Time in Comfort (PTC) from LadyBug® for Grasshopper®. We use HoneyBee® for Grasshopper® for ASHRAE Adaptive Comfort Calculations.

1.3.3 Summary of Methods adopted in Chapter 4

In this Chapter, the method is organized according to an interpretation of the methodology extracted from Cartana et al. (2018) and Fang (2017): (1) geometry optimization considering the elimination of non-robust parameters dismissed through factorial analysis in Chapter Three; (2) computational simulations for the admission of solar radiation and daylight performance for transitional spaces; (3) comparative evaluation of the best solutions generated in the simulation process.

Using the geometry created in Chapter Three, we connect the robust to Octopus®. The optimization process uses the engine to search for optimal building configurations for the maximum average Useful Daylight Illuminance (UDI) and minimum thermal discomfort expressed by Physiological Equivalent Temperature (PET).

In the second stage, we employ Honeybee® for computational simulations regarding the admission of solar radiation and natural light in the designated transitional spaces.

We run the simulations for three different transitional spaces and interpret and compare them.

1.4 Thesis Structure

We arranged the thesis into five chapters. Chapters two, three, and four are written in article writing format.

Chapter one presents the introduction and justification of the theme. It displays the objectives, a summary of all the methods adopted, and the dissertation structure.

In Chapter Two, we investigate Specific Objective A. The goal of this chapter is to appraise the design process of a modular canopy based on biomorphic shapes that allow radiation indoors, maximizing diffuse radiation and minimizing beam radiation according to solar geometry.

In Chapter Three, we answer Specific Objective B. This chapter intends to evaluate the design process of a modular canopy based on Origami complex shapes through computational simulation, radiation optimization, and statistical analysis.

In Chapter Four, we meet Specific Objective C. We strive to probe and perform a simulation-based optimization for an Origami-inspired canopy in transitional spaces. As optimization objectives, we employ the maximization of Percentage Comfort for Physiological Equivalent Temperature (PET) and average Useful Daylight Illuminance (UDI).

Chapter Five displays the conclusions of chapters two, three, and four. We also present an overall assessment that combines all the specific objectives, research contributions, work limitations, and recommendations for future studies on the topic.

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PARAMETERIZATION AND SOLAR RADIATION SIMULATION FOR OPTIMIZATION OF A MODULAR CANOPY

Parametrização e simulação de radiação solar para otimização de uma cobertura modular

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Abstract

This study perceives the developing process of a parameterization modeling in Grasshopper® for complex surfaces using building simulation, considering diffuse and beam radiation as the key-variables. The primary goal of this article is to create, simulate and optimize a modular, semi-opened canopy based in retro-studies of tree leaves as engineering structures. The method applied consisted of the definition of parameters and criteria for the optimization of the simulation process and was divided into three stages: a study of form, form parameterization, and simulation and optimization. Ladybug® for Grasshopper® plugin was used to carry out the simulations, and Octopus® was used as a motor for optimizing the final script. The object of study chosen was the process of creation of a canopy because, in hot and humid climates, such as in Brazil, the roofing areas are a critical part of the building envelopes that are highly susceptible to solar radiation and other environmental changes, thereby, influencing the indoor comfort conditions for the occupants. Although the final product was created for a specific climate zone, it can be applied to any other zones with a few changes in the parameters due to parameterization. As main results, the solar control devices contributed to a reduction of 86% of the annual average of hourly beam solar radiation while maintaining high levels of diffuse radiation.

Keywords: Ladybug. Pareto front. Optimization based on simulation.

Resumo

Este estudo compreende o processo de desenvolvimento de modelagem paramétrica em Grasshopper® para superfícies complexas na construção, utilizando, como critérios de desempenho, a radiação difusa e direta. O objetivo principal deste artigo é criar, simular e otimizar uma cobertura modular, semipermeável, baseada no estudo e interpretação de folhas de árvores como estruturas de engenharia. O método aplicado envolveu a definição de parâmetros e critérios para a otimização do processo de simulação e foi dividido em três estágios: estudo da forma, parametrização da forma e simulação e otimização. O plugin Ladybug® para Grasshopper® foi usado para realizar as simulações e o Octopus® foi adotado como motor de otimização. O objeto de estudo escolhido foi o processo de criação de uma cobertura, pois em climas quentes e úmidos, como no Brasil, as áreas de cobertura são uma parte crítica do envelope construtivo, altamente susceptíveis à radiação solar e outras mudanças ambientais, influenciando nas condições de conforto interno dos ocupantes. Devido à parametrização, o produto final, embora criado para uma zona climática específica, pode ser aplicado para quaisquer outras zonas bioclimáticas com poucas alterações nos parâmetros. Como principais resultados, o dispositivo de controle solar contribuiu para a redução de 86% da média anual de radiação solar horária para radiação direta, mantendo os níveis de radiação difusa.

Palavras-chave: Ladybug. Curva de Pareto. Otimização baseada em simulação.

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Introduction

"Considering the importance of buildings in the total energy consumption and the fact that the constructive envelopes are responsible for the thermal exchanges with the [external] environment, as well as the admission of natural light" (CARTANA; PEREIRA; MAYER; 2017, p. 1685), the energy performance of wrapping systems is becoming increasingly important in contemporary architecture, according to Fajkus (2013). In this situation, solar control elements can contribute positively to building performance.

Regarding thermal issues, Cho, Yoo and Kim (2014), evaluating the application of solar control elements, identify that the radiated heat gains in general office buildings in South Korea consumes around 33% to 40% of the energy of the construction from May to September with an annual cooling load reduction of maximum 19.7%. Also, Bader and Zitzler (2010) identify the possibility of reduction of beam radiation in 75%, considering the use of the mentioned control elements.

According to González and Fiorito (2015), the integration of natural light and energy performance with the design optimization process has always been a challenge for designers. Most environmental performance simulation tools require a considerable amount of time and interactions to get accurate results. Furthermore, combining goals has always been a problem because different software is required to perform detailed calculations.

As stated by Sadineni, Madala, and Boehm (2011), the buildings we find today are expected to achieve energy efficiency and environmental-friendly design. It is also a common sense that sustainable buildings should encompass various issues regarding energy, water, land and material conservation, as well as environmental pollution and the quality of environments. Despite this common sense, sometimes sustainability does not cover all facets of its object of study.

It is a consensus amongst Sadineni, Madala, and Boehm (2011), Konis, Gamas, and Kensek (2015) and Stevanović (2013), that building energy efficiency can be improved by implementing either active or passive energy efficient strategies. All these references, though, call out for environmental-friendly passive building energy efficiency strategies.

Passive solar design strategies aim to use solar energy to help to establish thermal comfort in buildings, dismissing the use of electrical or mechanical equipment.

Canopies account for large amounts of heat gain/loss, especially in buildings with a large roof area, notably in countries near the Ecuador Line, which is Brazil’s case, even though they usually are left aside.

Sunlight is considered the best source of light and it meets best human needs, according to Narangerel, Lee, and Stouffs (2016, p.379). This light penetrates the building by fenestrations that can be both on the facade and the roof. The insertion of radiation inside the building, when accurately calculated, significantly reduces the need for artificial lighting. "In fact, as the literature suggests, natural light provides an environment of better quality and influences the psychological and the way the mind responds, as well as the biological rhythm" (PESENTI; MASERA; FIORITO, 2015, p. 347).

According to Ogbulezie, Ushie, and Nwokolo (2017), diffuse solar radiation plays a vital role in determining light use efficiency, changing the color of the sky and baseline for diffuse solar radiation parameters such as diffuse photosynthetically active radiation, when dealing with photosynthetic organisms.

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"The accurate determination [...] of diffuse solar radiation parameter is required for many applications such as energy management, solar energy, light studies, architectural research [...]" (NWOKOLO; OGBULEZIE, 2018, p.355).

According to Brotas and Rusovan (2013), architects rely on computational tools to investigate forms and structures. Likewise, these tools cannot only be used for shape generation but also to predict the performance of spaces. "On the one hand, environmental awareness and climate change have affected building regulations. They are increasingly becoming more demanding in terms of energy efficiency and promoting the reduction of CO2 emissions" (BROTAS; RUSOVAN, 2013, s.n.).

Krüger and Laroca (2009), who state in their work that over the last decades, several types of research were concerned with the simulation and evaluation of small systems or individual systems in a building, endorse this statement. "In tropical and subtropical climates, the thermal performance evaluation [...] should be primarily related to the optimization of indoor comfort conditions [...]" (KRÜGER; LAROCA, 2009, p. 661).

In fact, in the last decades, according to Delgarm et al. (2016), considerable research was directed to optimization based on simulation, in order to understand the construction parameters and appropriate architectural configurations to promote its energy efficiency. Besides, Fonseca et al. (2016, p. 267, our translation) state that, "the development of computational technology has led the optimization associated with the parameterization to enable the development of projects with better performance, with or without integration with the simulation."

Over the past twenty years, the work of creating solar protection, regardless of the face of the building, was manual, and variations such as latitude, longitude, building rotation, geometry modification, and others, required analog rework. According to Eltaweel and Su (2017), in the contemporary conception of architecture, all these aspects in their dimensions can be considered parameters and with the application of the correct software, it is possible to assemble a complete base, which can be altered and improved with efficiency, so that the design of the building simultaneously changes without rework. Jakubiec and Reinhart (2011) share these same thoughts.

The term parametric originates from mathematics and refers to using specific parameters or variables, which can be amended in order to manipulate with the equation results. Eltaweel and Su (2017, p. 1087) state that, "[...] the principle of parametric design can be defined as a mathematical design, where the relationship between the [...] elements are shown as parameters which could be reformulated to generate complex geometries [...]". These geometries are based on the elements' parameters. By changing these parameters, new shapes are created simultaneously.

Andrade and Ruschel (2009) have identified that publications on the use of parametric modeling programs have emerged no more than a decade in Brazilian Conferences. Santana, Guimarães and Carlo (2015) infer that, although parameterization has been applied to energy efficiency studies for almost two decades in Brazil, the evaluations that take into account shape parameters are recent due to the computational advances implemented in the current decade.

Nowadays, parametric design is used in many fields, disciplines that consist of complex algorithmic relations, interdisciplinary work, creative forms, and multiprocessing treatments such as AEC (Architecture, Engineering, and Construction). It is not easy to control these operations using conventional tools or imagine them using our analogical thinking, so it is needed to use complex operating systems, parametric tools, and specific software. Due to this digital and technological development, we can find many

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implementations of parametric design in many fields like decoration, fashion, architecture, urban planning, sonic study, structural analysis, medicine and so on (ELTAWEEL; SU, 2017, p. 1090).

Eltaweel and Su (2017) state that daylight and radiation are influenced by many divergent criteria such as longitude, latitude, sun path, sky type, solar radiation, humidity, territory, among others. All of these aspects have different parameters and are influenced by each other. Therefore, parametric design can provide this utility by connecting these data using specific software, which can ease the design decision, modeling, and solving problems. Furthermore, it could anticipate the optimum solutions for the building design especially via analyzing the influence of daylight.

“Studies have demonstrated the potential use of tools to analyze the performance of the constructive envelope for energy optimization or visual aspects” (FELIPPE et al., 2015, p. 398) and because of the repetitive nature of the procedures, to achieve them, this optimization is automated. In short, modeling software Rhinoceros 3D®, its DIVA® plugin, Ladybug®, HoneyBee®, Grasshopper®, and EnergyPlusTM building-modeling programs are often cited.

According to Gossard, Lartigue, and Thellier (2013, p. 253), "improving the thermal performance of a building can be done in two ways. The first approach is based on a trial-and-error method […] and the second approach ensures a more reliable method by using optimization algorithms". Although the "’trial-and-error’ processes may be able to generate acceptable solutions, they are doubtful to achieve near-optimal designs" (MAGNIER; HAGHIGHAT, 2009, p. 739). For this reason, the optimization using genetic algorithms is seen as an option with higher chances of indicating the best solutions for a project according to its objectives and constraints.

With the advances in computational design, parametric optimization and building performance simulation, researchers such as Eltaweel and Su (2017) and Pesenti, Masera and Fiorito (2015), believe that what is necessary for the continuous development of generative methods with integrated approaches is only to explore the project from biases that have not yet been explored.

As claimed by De Focatiis and Guest (2002), the analysis of tree leaves as engineering structures is a relatively recent one. Most leaves can be modeled as thin membranes or laminae with reinforcements in the form of veins and midribs. “The leaf is a compromise in flexibility and rigidity. It is the interaction of these stiffening members and the flexible membrane panels that leads to an interesting mechanism” (DE FOCATIIS; GUEST, 2002, p. 227).

The advantage of the leaf-folding patterns can be seen when several membranes of the leaf are joined to produce polygons. “The leaves can be arranged in two basic ways, either pointing towards the center of the polygon, leaf-in, or directed away from it, leaf-out” (DE FOCATIIS; GUEST, 2002, p. 228). The folds of different leaves can be interconnected and are compatible with each other. This way, the whole structure can be folded and unfolded from a single or multiple driving points.

In conclusion, the goal of this paper is to evaluate the process of creation of a modular canopy based on biomorphic shapes, capable of allowing the entry of radiation indoors, maximizing diffuse incident radiation per m^2 and minimizing beam radiation according to solar geometry, through computer simulation.

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Method

This research is of quantitative and exploratory type (GROAT, 2013) inserted in the area of Performance-Based Design, involving simulations for radiation and optimization. Methods aiming at the analysis of a design process based on optimization are emphasized. For instance, the method adopted by Pesenti, Masera, and Fiorito (2015) and González and Fiorito (2015) were the main ones used in this study, because of the approximation to the study of forms applied to complex surfaces. Thus, the research was divided into three stages. The first stage concerns the exploration and definition of the form; the second stage regards the parameterization of the canopy and the third stage concerns simulation for radiation and optimization of the design.

First Stage

The work was carried out following an interpretation of the methodology applied by authors such as Pesenti, Masera and Fiorito (2015), Cheng et al. (2015), ElGhazi and Mahmoud (2016) and González and Fiorito (2015) and was divided into three parts. The first part follows the bias of the investigation of the form. This is a critical phase for the project since the design must start from a simplified approach so that its reproduction can occur without difficulty, given the formal complexity usually applied in parametric geometries.

Academic research evidenced by Pesenti, Masera and Fiorito (2015), Mahmoud and ElGhazi (2016) and De Focatiis and Guest (2002), contemplate geometric forms based on origami and branches and leaves, since the kinematics created by the fold of the geometries surpasses the variety of angles allowed by a Euclidean geometry, besides being considered adaptive forms. It is a system that easily deforms, creating patterns capable of reducing the use of material, increasing structural rigidity and retaining lightness, one of the principles discussed by Buckminster Fuller's theory of "Tensegrity"(1).

In some leaves and flowers, a folding technique is used efficiently to optimize their shapes continuously. De Focatiis and Guest (2002, p. 227) point that “Hornbeam and Beech leaves have a particularly simple and regular corrugation pattern [...] that is strengthened by the distortion induced in the cantilevered corrugation”. Thanks to that, they have been taken as inspiration for engineering structures. Hornbeam, Beech and Maple leaves exhibit a deployment mechanism; the pleats are disposed like V-shaped patterns in a way to allow young leaves to fit into the buds.

In the opinion of Pesenti et al. (2015, p. 663), leaves motion, like Oxalis Triangularis, has to be considered as nastic movements, “where active structures respond to an external stimulus independently of direction, inducing a reversible movement – the folding/unfolding of the leaf.” Therefore, learning from nature may be particularly useful for a biomimetic translation into the design of a kinetic shading device.

For this research, forms of nature were used, more specifically, abstractions of leaves (Figure 1) as a starting point, taking into account their organicity and ability to behave hastily, while creating protection from weather, one of the premises of the project.

It consists in the use of Rhinoceros 3D® and Grasshopper® to assemble a script that allows variation of the design according to its geographical positioning.

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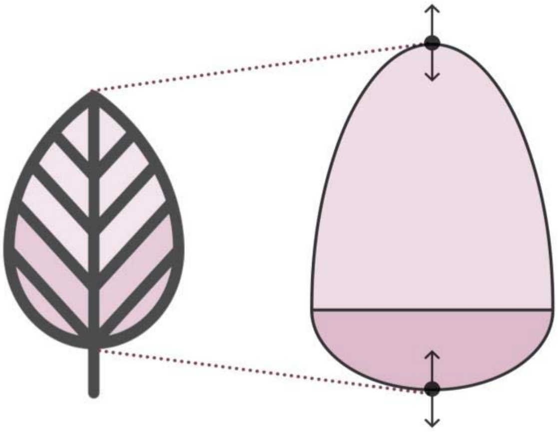
Figure 1 - Creation of shape based on the leave natural form. Division indicates the upper and lower dampers

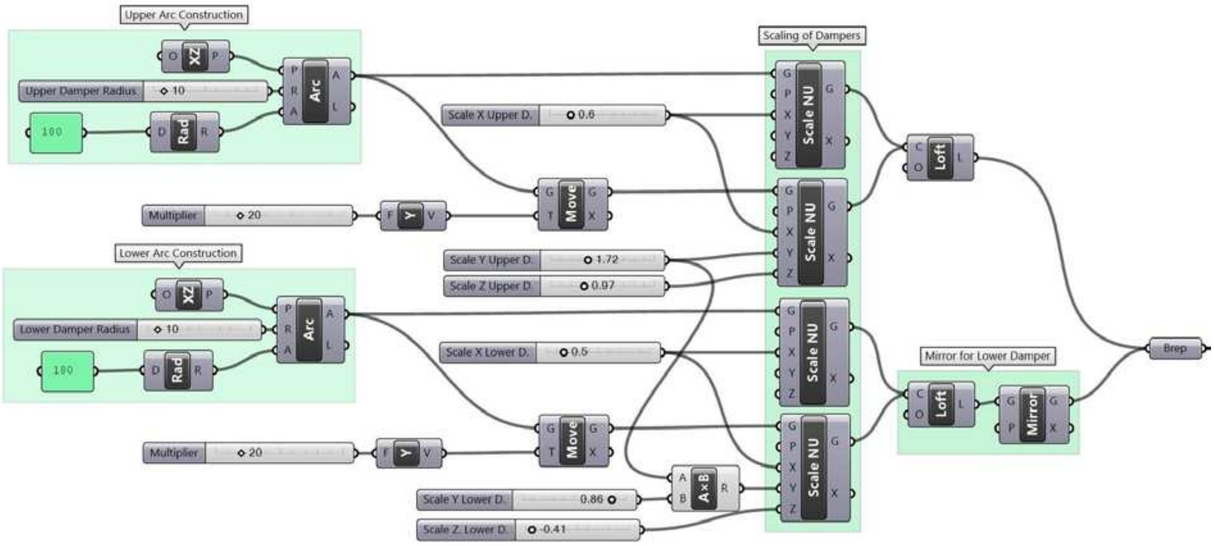


Font: The authors.

Second stage

The variability of the project is based on the possibility of implantation of it in different latitudes and longitudes, depending on the weather file used. In this experiment, the weather file TMY3 for the city of Viçosa (Latitude 20° 45' 14" S, Longitude 42° 52' 55" W, Altitude 648 m), MG, was used (GUIMARÃES, 2016). The purpose of creating this script is that, with the modification of small parameters (Figure 2), such as module size, height, angulation, opening area, among others, it is possible to generate an optimized form. This modification is allied to the solar masking for the specific latitude in which the project is located.

Figure 2 - Script relationships in the Grasshopper® plugin adding the multiplier to the number slider and to the scale in Y-axis, preventing upper damper to be larger



Font: The authors.

The initial module was divided into two parts, and two modifiable parameters were applied for each of these parts (Figure 3). Thus, the module can vary in aperture and length at its top or bottom. For its lower part not to be larger than the upper one, and then to prevent entering radiation and to avoid water accumulation on the inside damper, a multiplier has been added (Figure 2). Its Y scale factor will depend on two values, which are the scale and the multiplier, a diminishing factor.

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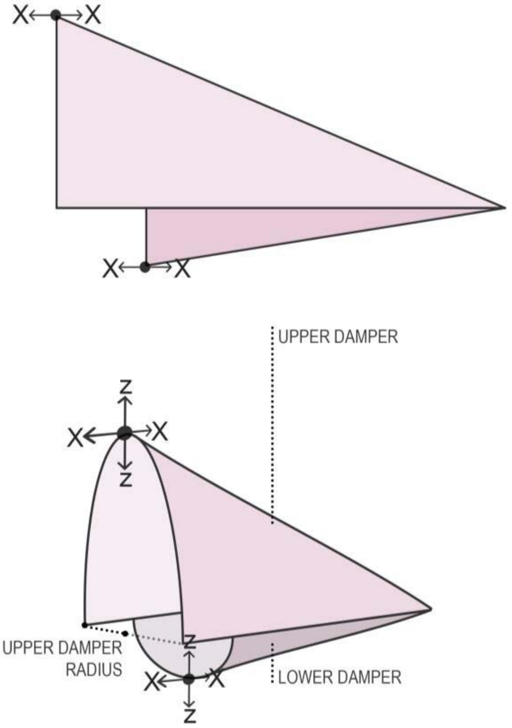
Figure 3 - Module and axis of movement. In the module, variations in size are represented in X and Z-axis, while Y-axis is maintained unchanged



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All openings are facing north to allow beam radiation incidence in the case studies, leading to cases in which this radiation will be minimized.

Considering the need to measure the levels of beam and diffuse radiation, a plan of analysis was created just below the structure of the Canopy (Figure 4), much smaller than the extension of the modules, so that the radiation coming from the sides of the structure would not reach it and affect the final calculations. For the evaluation of the radiation, the plugin Ladybug® for Grasshopper® was used.

According to Cheng et al. (2015, p. 323), analyzing solar radiation of simple motifs is the first step in a simulation, helping with the understanding of the following situations. The efficacy of these simulations can be interpreted and help initiate design decisions for building skins. The quantitative results from radiation simulations can improve understanding of the consequences of complex patterning, driving design refinement. (KHORASGANI; BURRY; SALEHI, 2014).

LadyBug® was chosen for the radiation analysis because, according to Roudsari and Pak (2013), Ladybug® imports standard EnergyPlus Weather files (.epw) into Grasshopper® plug-in and provides a variety of 2D and 3D interactive graphics to support the decision-making process during all stages of design. It also simplifies the analysis process, automates and expedites the calculations, and provides easy to understand and to manipulate graphical visualizations in the 3D modeling interface of Rhino/Grasshopper®. “It also allows users to work with validated energy and daylighting engines such as EnergyPlus, Radiance, and Daysim” (ROUDSARI; PAK, 2013, p. 3128).

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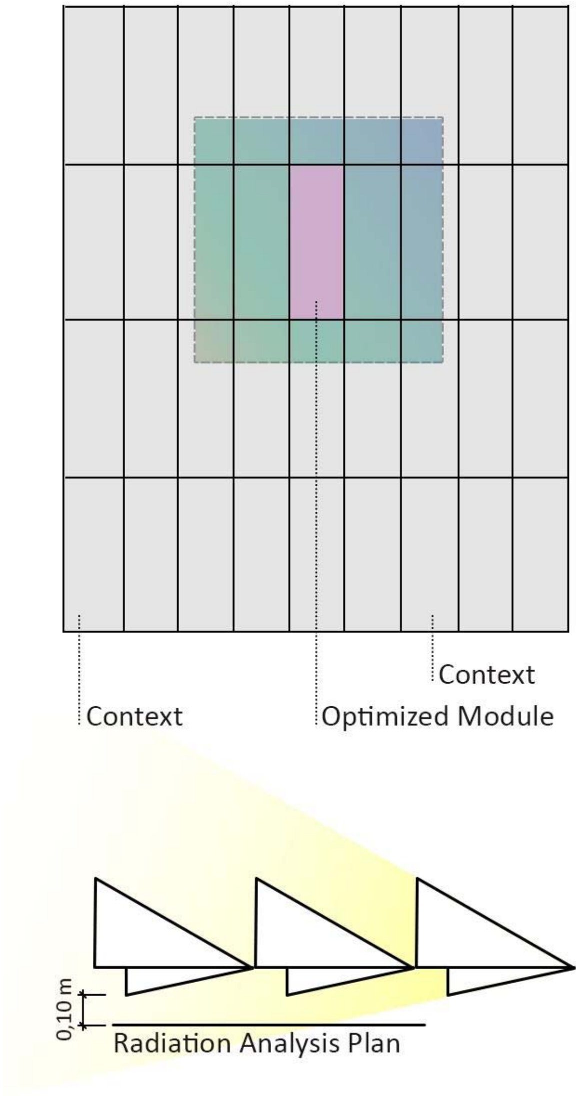
Figure 4 - Top view of modules and analyses plan for radiation and the treatment received by the modules



Font: The authors.

Third stage

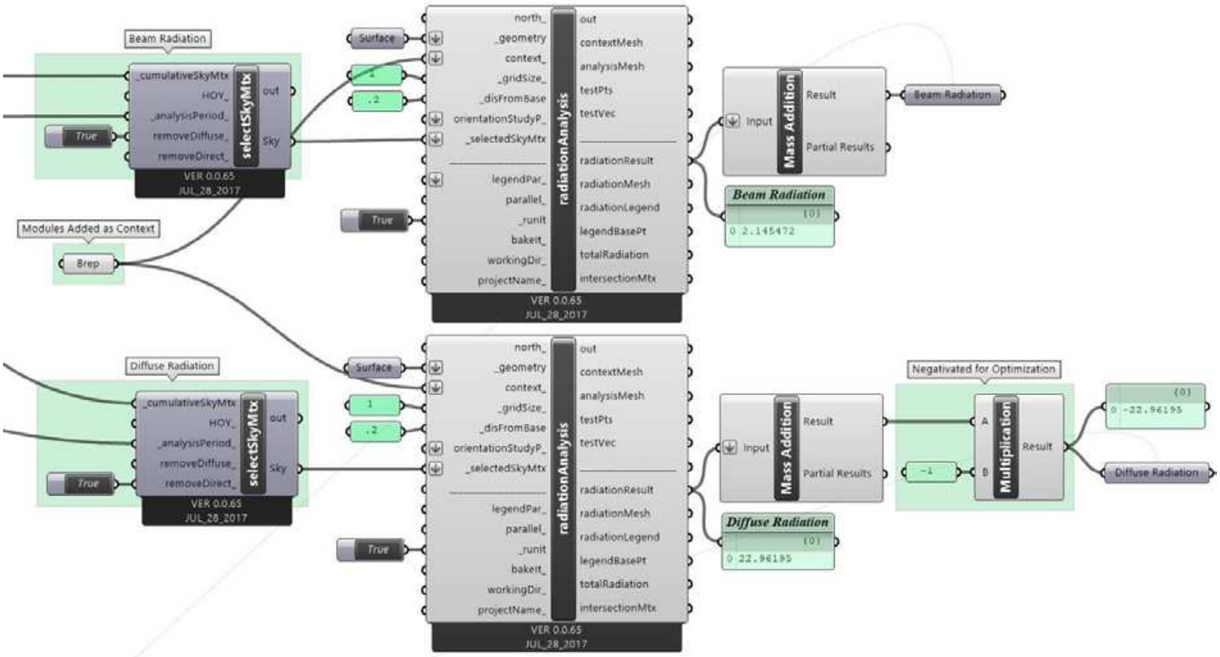
It regards the simulation and optimization using Ladybug® and Octopus® plugins for evaluation of the incident radiation per square meter. According to Fonseca et al. (2017, p.267), Octopus® "enables the user to work with two or more goals, such as the 'diversify parameters' option", which increases the chances of algorithm exploration in the entire search field of solutions. Octopus® plugin for Rhino® also allows the use of two genetic algorithms in the optimization: HypE or SPEA-2. The plugin "also makes it possible to determine the size of the population that will be created within each generation" (FONSECA et al., 2017, p. 267), allowing the user to establish a maximum number of generations. In this study, SPEA-2 was used.

According to Zitzler, Laumanns, and Thiele (2001), SPEA-2 is an elitist evolutionary algorithm created by the authors mentioned above that present evolution when compared to his predecessor. It was tested and compared to its predecessor and other two popular genetic algorithms based on elitist methods (PESA and NSGA-II) and presented promising results.

Considering the use of Ladybug® and its capacity to evaluate radiation we chose to work with diffuse radiation maximization and beam radiation minimization (Figure 5), composing a multi-objective optimization.

According to Nguyen, Reiter, and Rigo (2014), optimization can be classified according to the number of objective functions. It can be a mono or multi-objective optimization, although Nguyen, Reiter, and Rigo (2014) identified that 60% of building optimization studies had only one objective function. Multi-objective optimization, on the other hand, approaches more of real problems, since designers usually need to deal with conflicting design criteria (NGUYEN; REITER; RIGO, 2014).

Figure 5 - In the script relations is noticed that the first box of radiation has a true Boolean Toggle for removing diffuse radiation while in the second one, the true Boolean Toggle is removing the beam portion of the radiation



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According to Evins (2013), evolutionary algorithms are amongst the most common in optimization. They are based on Darwin's theory of evolution, in which populations of solutions are created, and each of these is evaluated according to their performance. They use a principle of "natural selection to evolve a set of solutions towards an optimum solution" (MACHAIRAS; TSANGRASSOULIS; AXARLI, 2014, p. 103). With each generation created, the poor performers are eliminated from the population (EVINS, 2013), while the best are kept for the next generation creation and selection process.

According to González and Fiorito (2015, p. 561), they use techniques such as "inheritance, mutation, selection, and crossover to evolve a solution for general or specific problems." They have been proven to be an effective strategy for addressing multi-objective design problems and calculate multiple performance criteria, finding close to optimum solutions in a short period. However, their application requires extensive mathematical and computer programming knowledge, far beyond the domain of most professionals. The creation of Octopus® has filled this gap.

This part of the methodology combining Octopus® with performative plugins could be one of the answers to ensuring high levels of environmental performance while reducing the time needed for extensive trial and error processes. “Simulations can be performed automatically and the results stored and organized according to their performance” (GONZÁLEZ; FIORITO, 2015, p. 561).

For data analysis, Vilfredo Pareto proposes one of the most popular methods to present multi-objective solutions. “A solution is Pareto optimal or nondominated when there isn't any other feasible solution that improves one objective without deteriorating at least another one” (MACHAIRAS; TSANGRASSOULIS; AXARLI, 2014, p. 102). When the problem consists of two objectives, the Pareto frontier can be represented as a curve.

Also known as Pareto Analysis, the ABC Curve is a method used to organize points in order of relevance, in which 20% of the factors usually cause 80% of problems. For the analysis of the data collected in the simulation and optimization, one of the methods consisted of the creation of an ABC Curve.

“The ABC curve is a method of classifying information, so that items of greater importance or impact are separated, which are usually in smaller numbers” (CARVALHO, 2002, p. 226). It is a statistical classification of materials based on the Pareto principle, which considers the importance of materials based on the quantities used and on their value.

To divide total radiation into two plots it was necessary to break the script into two parts, one containing a true toggle only for the beam plot of radiation, and the other containing a positive toggle only for the diffuse plot of radiation (Figure 5). In the Octopus® plugin, a third objective was added by asking for Diversification of Parameters in order to ensure that the optimization engine searches the entire solution space and does not run the risk of being stuck in a local search, which could lead to a loss of potential solutions.

The parameters used were movement in the Y and Z-axis in the upper and lower damper, as it was discussed earlier in the paper, totalizing four parameters besides the diversify parameters.

Octopus® is started with a population size of 100 and Max generations of 50 to make optimization feasible. The plugin allows the user to choose a solution for analyzing parameters and performance indicators visually. According to Fonseca et al. (2017, p. 267) “its relevance as an optimization engine for Grasshopper® is also to avoid that the optimization is interrupted when faced with cases impossible to reach a viable solution.” It automatically skips the case if the user determines a maximum evaluation time for each simulation.

During the simulation, the convergence of solutions will be used as a stop criterion. The point of convergence is defined by looking at the graph provided by Octopus®.

Results and discussion

The convergence of the model occurred in generation 33 (Figure 6). The first Parameter Graph (a) is from the first generation and the second (b) is from the thirty-third generation when the convergence is seen. The units concern to the annual average of hourly solar radiation considering 12 hours of daylight, using the TMY3 Weather File for Viçosa (Latitude 20° 45' 14" S, Longitude 42° 52' 55" W, Altitude 648 m) (GUIMARÃES, 2016). In the parameter graph, each solution is presented as a line connecting the parameters; the closer the lines, the more the project approaches convergence.

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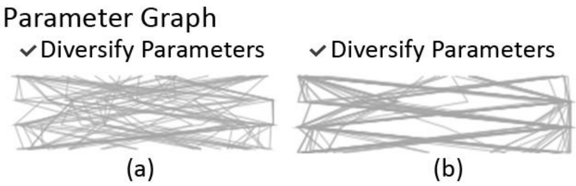
Based on the data provided, a dispersion graph was created for further analysis (Figure 7). According to Delgarm et al. (2016, p. 295), "[…] in the multi-objective optimization problems, all points on the Pareto front are potentially an optimum solution".

In this respect, the selection of the final optimum configuration among the available optimal points requires a process of decision-making.

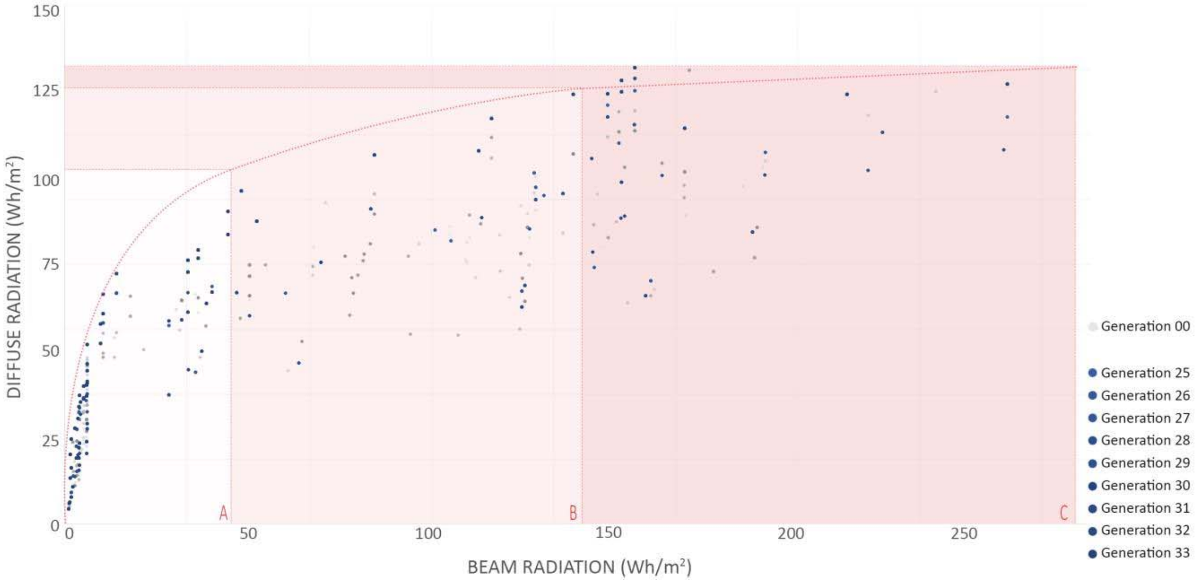
Figure 6 - Parameters convergence of generation 01 (left) and generation 33 (right)



Font: The authors.

The graph (Figure 7) is divided into three classes: A, B, and C. In class A, the elements found have greater importance, value or quantity, corresponding to 20% of the total, class B has intermediate importance, quantity or value and corresponds to 30% of the total, while class C corresponds to 50% of the total and has minimum status. Taking into consideration the Pareto Frontier, the results that form the curve are considered a non-dominated solution, even though any other point in the Figure 7 could be considered feasible solutions, according to Machairas, Tsangrassoulis and Axarli (2016).

Figure 7 - Optimization Curve (Pareto Curve or ABC Curve). The color label presents 9 last generations. Label for generations 0 to 24 was condensed



Font: The authors.

As seen in the Pareto front, most results close to the convergence are in group A, and a small amount of them is in group B (Figure 8).

Taking into account that the optimization concentrates the best results in the last generations and that the best results are found in Group A according to the ABC curve, three solutions were selected as the best ones because of their higher diffuse radiation values (Figure 9).

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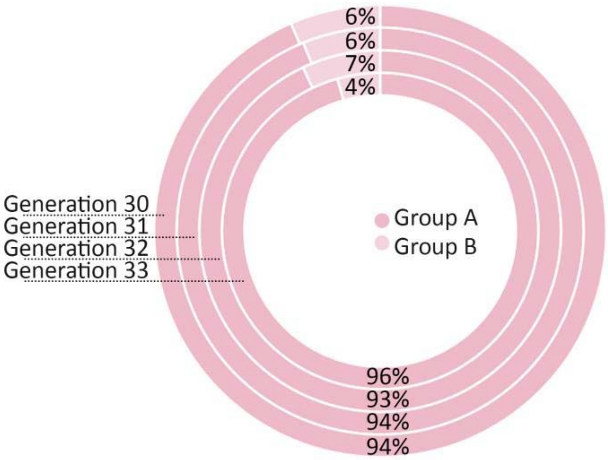
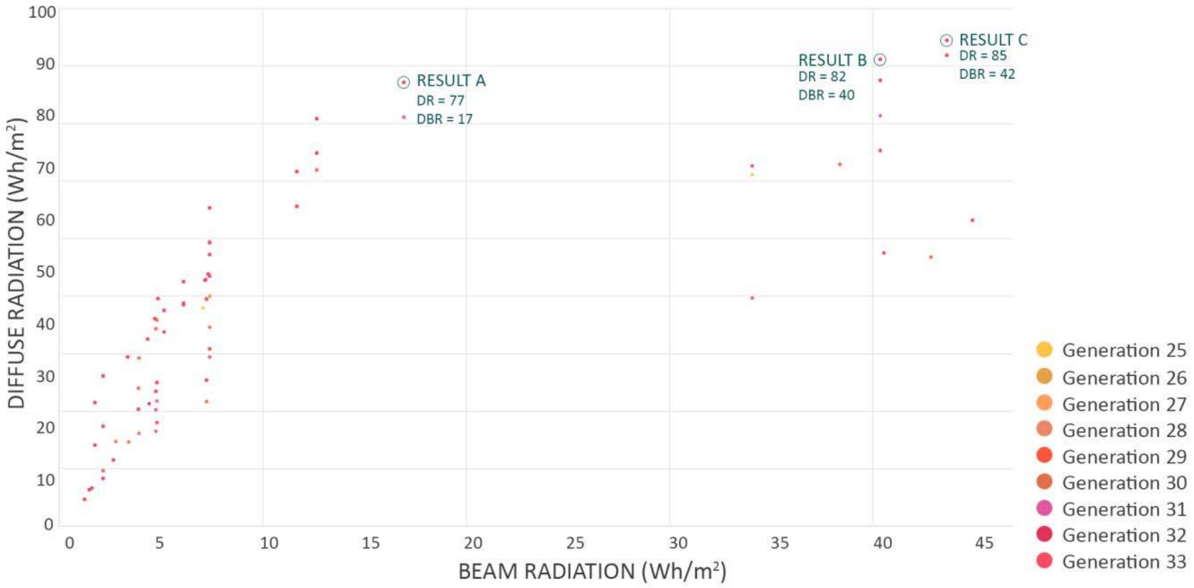
Figure 8 – Four last generation's placements in the ABC Curves



Font: The authors.

Figure 9 - Optimization Curve (Pareto Curve or ABC Curve) – 20% best results. The color label presents generation 25 to 33



Font: The authors.

Among the diffuse solutions that were not chosen, the annual average reached up to 175 Wh/m2 for hourly diffuse and 85 Wh/m2 for hourly beam radiation. It can be seen that the optimization kept diffuse radiation high, reaching and surpassing the average annual values.

This can also be seen while comparing the simulation results to the hourly solar radiation obtained from the TMY3 file. The weather file diffuse radiation (Figure 10) presents higher values in the rainy summer and especially in spring hours, December to March and September to December respectively. It also presents a valley in the winter season, June to September. The optimized results of the annual average of hourly radiation below the canopy for the solutions of the last generation reached values comparable to spring and summer, about 175 Wh/m2, which means a reduction of 20% compared to the highest level of diffuse radiation. For the optimized results, there is a reduction of 14.5%

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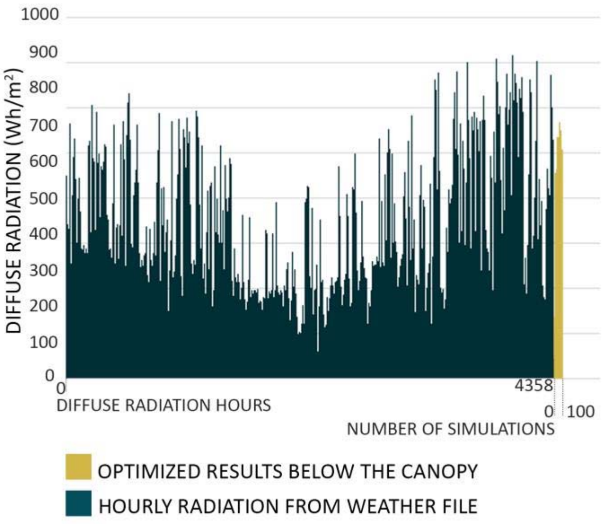
for result A, 8.8% for result B and 5.5% for result C, when compared to the annual average.

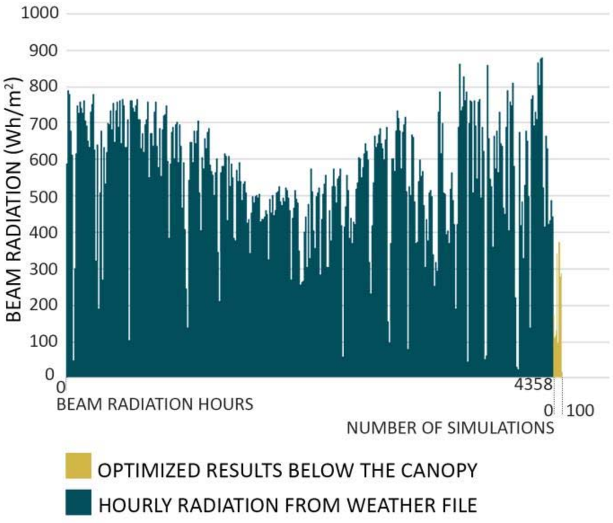
Figure 10 – Hourly diffuse radiation from weather file and annual average from the solutions of the last generation



Font: The authors.

For beam radiation (Figure 11), there is also a peek in summer and spring hours with a low bound during the winter time. Since the scope of the optimization was to minimize beam radiation and maximize the diffuse portion, the levels of radiation achieved were as low as 17 Wh/m2 for result A, the equivalent of a reduction of 94.5% when compared to the weather file annual average. For result B, beam radiation was 40 Wh/m2, a reduction of 87.5% and for result C, beam radiation was 42 Wh/m2, and the reduction was of 86.8%.

Figure 11 – Hourly Beam Radiation from weather file and annual average from the solutions of the last generation



Font: The authors.

When it concerns the parameters, the input data in Grasshopper® for the results shows a low variation of values for some parameters and a high variation for others (Figure 12). Therefore, one to believe that the optimization depended on the combination of parameters 1, 2 and 3, responsible for scale in Y and Z-axis for the upper damper and

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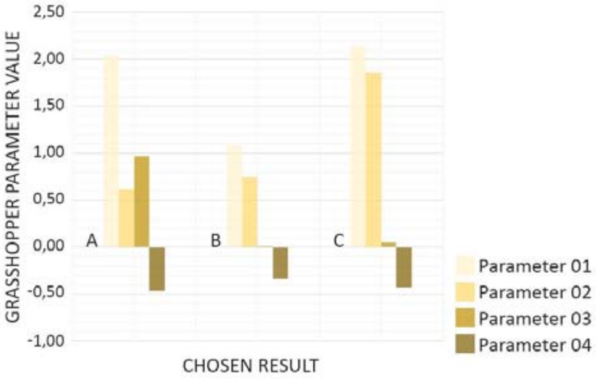
scale in Y-axis for the lower damper, with the multiplication factor, respectively. Parameter 4, responsible for scale in Z-axis for the lower damper, had little effect in the optimization.

Figure 12 – Comparison of variability of parameters input data for three chosen results



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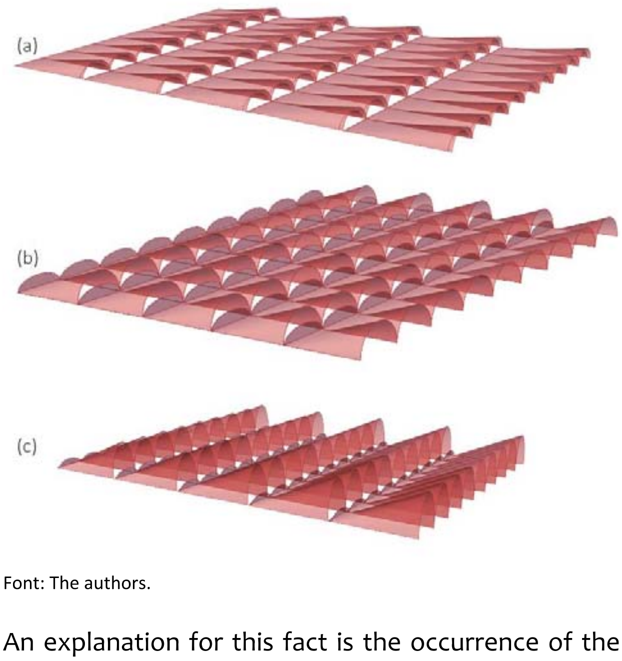
The analysis of the best results in the four last generations is consistent with the evaluation of all the results, which implies that the Z-axis values for the lower damper were not definitive for the result and it confirms what was designed (Figure 13). The three selected results are shown in order and, in all three results, we can see that the bottom damper of the model was not maintained in the bottom portion of the module, due to the optimization process.

Figure 13 - Three canopy geometries generated and chosen in the optimization process



Font: The authors.

An explanation for this fact is the occurrence of the reflection on the outside of the module, mainly in the upper damper, and not in its interior, as imagined at the beginning of the study. In order to avoid the direct portion of radiation, the model inverted the bottom lappet, creating an upper flap. Thus, the lower damper was automatically

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incorporated to the upper part of the module, helping diminish the portion of bean radiation penetrating the canopy.

Conclusions

To design is to anticipate the creation of forms in the material world. In order for the project to be thought and transmitted to all participants in the process, it has to be represented in 2D and 3D. Consequently, the architect should materialize its ideas into representations.

Computational optimization can differ from traditional methods, providing new answers for design problems that can be more effective in solving specific tested issues.

For the studied case, the optimized solution performs significantly better regarding radiation availability, having the beam portion of radiation below the canopy diminished up to 94.5% for the best-case scenario when compared to the annual average, maintaining diffuse radiation close to the average values of the weather file for all of the chosen solutions. For cases B and C the hourly beam radiation under the canopy was diminished by 87.5% and 86.8% respectively.

The results presented as Pareto solutions in the ABC curve indicated the importance of the designer's decision, primarily in the choice of the final solution, since the curve and the selection of data have to be made by the researcher.

The tools used in the simulations and optimization, although not yet ingrained among designers and presenting limitations, proved their potential for integration between the design process and specific areas in architecture and engineering, such as performance analysis.

Besides, because the software and the plugins used are recent technology amongst architects and engineers, there is a promise of rapid advance in the next 10 to 20 years. Several of the computational tools used are in the improvement phase and have been updated during the development of the model.

This project is an exploratory project of the potential application of the tools used to optimize the dimensions of the modules of a canopy, to satisfice radiation solutions following a straightforward application of parameters.

Future studies can be built upon the current one and explore an expanded set of optimization criteria, combining energy-related indicator with visual comfort ones, such as glare probability and uniformity of daylight illuminance. In conclusion, the results demonstrate that the integration of computational design and performance simulations for solar control elements with complex shapes is essential for selective admission of solar radiation.

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Notes

(1) According to Calladine (1978), in the first decades of the twentieth century, kinetic architecture was completely theoretical. In 1940 innovators, such as Buckminster Fuller, began experiments in this area, even if unsuccessfully. Despite this, much of what was produced by Fuller was used. His theory known as "Tensegrity" was incorporated into robotics, popularized in the 1980s. This theory was based on the combination of simple designs in pure traction or compression.

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Research Article

Parametric modeling simulation for an origami shaped canopy

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KEYWORDS
Parameterization;
Radiation analysis;
ASHRAE adaptive comfort;
Statistical analysis;
Complex surfaces

Abstract This study perceives the developing process of a parameterization modeling in Grasshopper® for complex surfaces using building simulation, considering Annual Average of Hourly Radiation as the key-variable. The major goal of this article is to create, simulate and analyze through factorial analysis a modular canopy, based on Origami. The methodology applied consisted of the selection of the form, canopy parameterization, factorial analysis and simulation for radiation. Ladybug®, together with EnergyPlus™, were used to carry out the simulations. The object of study was the process of creation of a canopy. In countries with hot and humid climates, such as Brazil, the roofing areas are critical parts of building envelopes, highly susceptible to solar radiation. The simulation was performed for a full year for Viçosa, MG (Latitude 20° 45′14″S, Longitude 42° 52′ 55″ W, Altitude 648 m), but due to parameterization, the canopy can be simulated anywhere else. As main results, the factorial analysis contributed for determining that the slope of the canopy was the most robust factor to the detriment of the cardinal and collateral orientations. For the best case scenario, the simulation generated levels of comfort of about 74.0% with 15.4% Hot and 10.6% Cold for natural conditioned spaces.

1. Introduction

The growing awareness of the impact of buildings on energy consumption and indirect carbon emissions is generating an interest among practitioners in developing projects that go beyond energy compliance limits to maximize optimization. Instead of analyzing and choosing from a range of possible solutions, as shown by Sadineni et al. (2011), designers must predetermine the failure of the building design in the early stages to obtain fast and interactive feedback.

According to Delgarm et al. (2016), "energy is one of the most important resources used by the modern society and is the core of the economic and social activities in the industrialized countries" (Delgarm et al., 2016, pp. 293).

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Over the past 50 years, we have seen a large increase in global energy demand for industrial development and due to population growth. Therefore, improvements in energy efficiency have become an important international business, for both designers and researchers.

This article is circumscribed to the steps of developing a performance-based canopy inspired by Origami shapes. It takes into account the discussion on how the energy and other related simulation approaches are necessary for performance evaluation and parameterization of the form in the primary stages of design. The first aspects considered were the form of the object and solar radiation. Considering design aspects, such as scaling in *X* axes, scaling in *Y* axes and deviation, as optimization parameters, it is possible to modify the surface of the canopy in order to achieve the objective of reducing beam radiation, and maximizing diffuse radiation. The optimization parameters are selected through the use of statistical analysis.

This paper aims to evaluate the process of creation of a modular canopy based on Origami shapes and complex surfaces, capable of allowing the entry of radiation indoors, thus maximizing diffuse incident radiation per square meter and minimizing beam radiation, according to solar geometry, through computer simulation, radiation optimization and statistical analysis.

2. Literature review

2.1. Energy consumption and daylighting

"Considering the importance of buildings in the total energy consumption and the fact that the constructive envelopes are responsible for the thermal exchanges with the [external] environment, as well as the admission of daylight" (Cartana et al., 2018, pp. 1684, our translation), the energy performance of wrapping systems has become increasingly important in contemporary architectural production, according to Fajkus (2013). In this scenario, shading strategies can contribute positively to the performance of buildings.

According to Sadineni et al. (2011), "a significant portion of the energy is consumed by today's buildings" (Sadineni et al., 2011, pp. 3618). This highlights the imperative need for energy savings. Therefore, shading devices can contribute to improve building performance.

Regarding thermal issues, Cho et al. (2014), evaluated the application of shading devices and identified that the radiated heat gains in general office buildings in South Korea accounted for about 33%—40% of the energy consumed by the construction sector from May to September, with annual maximum cooling load reduction of 19.7%. According to the International Energy Agency (IEA, 2010), the same buildings currently account for 40% of the energy consumption in most countries. A significant part of it is used for heating and cooling systems to bring comfort to the users of the buildings. In addition, Bader and Zitzler (2011) state that beam radiation may be reduced in the order of 75%, considering the use of the mentioned control elements, with good visual access to outdoors.

Sadineni et al. (2011) provide an exhaustive technical review of the building envelope components for the potential of their passive energy savings. They state that roofs are critical parts of the building envelope and are highly susceptible to solar radiation and other environmental changes, which affects indoor comfort conditions. Canopies account for substantial heat gain/loss, notably in countries near the Ecuador Line, including Brazil, despite the fact that they are usually left aside.

Jakubiec and Reinhart (2011) observed that solar shading elements can also improve the distribution of natural light and reduce the likelihood of visual discomfort. According to Reinhart and Wienold (2011), an integrated assessment of the luminous performance of a building should consider the annual availability of natural light, visual comfort and thermal loads in the form of radiation analysis. "Daylighting design hence becomes a tradeoff between optimizing the annual daylight availability within a space while making sure that the space is energy efficient and exhibits high occupant satisfaction." (Reinhart and Wienold, 2011, pp. 387).

2.2. Computational design process

According to Brotas and Rusovan (2013), architects rely much on computational tools to investigate forms and structures. Likewise, these tools cannot be used only for shape generation, but also to predict the performance of spaces.

As stated by González and Fiorito (2015), the integration of daylight and energy performance with the design simulation process has always been a challenge for designers. Most environmental performance simulation tools require a considerable amount of time and interactions to obtain accurate results. "Moreover the combination of daylight and energy performance has always been an issue, as different software packages are needed to perform detailed calculations." (González and Fiorito, 2015, pp. 560).

The first decade of the 21st century has seen multiple advances in the numerical analysis of the overall performance of daylit spaces, according to Mardaljevic et al. (2009). These advances include more refined glare prediction and simulation methods, distribution of natural light and radiation analysis. These innovations stand in harsh contrast to current daylighting design practice, which, according to Reinhart and Wienold (2011), "still favors the use of rules of thumb during schematic design and largely relies on the daylight factor" (Reinhart and Wienold, 2011, pp. 386) and illuminance distributions under unreal circumstances of clear sky conditions during solstice and equinox days.

Regarding model simulation, according to Agirbas (2017), "[...] [they] can be described as an experimental environment which, depending on the time, enable inferences to be drawn on the basis of exact or approximate information" (Agirbas, 2007, pp. 325).

Krüger and Laroca (2010) state that, over the first decades of the 21st century, several research works focused on the simulation and evaluation of small systems or individual systems in a building. "In tropical and

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subtropical climates, the thermal performance evaluation [...] should be primarily related to the optimization of indoor comfort conditions [...]" (Krüger and Laroca, 2010, pp. 661).

Over the past twenty years, the creation of shading devices, regardless of the face of the building, was manual, and variations such as latitude, longitude, building rotation, geometry modification and others, required analog rework. According to Eltaweel and Su (2017), in the contemporary conception of architecture, all these aspects can be considered parameters and with the application of the correct software, it is possible to assemble a complete base, which can be altered and improved efficiently, so that the design of the building simultaneously changes without rework.

The term parametric originates from mathematics, and refers to using certain parameters or variables, which can be amended in order to manipulate with the equation results. Eltaweel and Su (2017) state that,

> [...] the principle of parametric design can be defined as mathematical design, where the relationship between the [...] elements are shown as parameters, which could be reformulated to generate complex geometries. [...] By changing these parameters, new shapes are created simultaneously. (Eltaweel and Su, 2017, pp. 1087)

The integration of parametric design with performance simulation tools gave the user the ability of testing, comparing and selecting the best solution for multi-objective problems, as the ones found in the built environment (González and Fiorito, 2015).

> Nowadays, parametric design is used in many fields, disciplines that consist of complex algorithmic relations, interdisciplinary work, creative forms, and multiprocessing treatments. [...] Due to this advancement in our life, we can find many implementations of parametric design in many fields like decoration, fashion, architecture, urban planning, sonic study, structural analysis, medicine and so on. (Eltaweel and Su, 2017, pp. 1090)

In architecture, according to Eltaweel and Su (2017), parametric design can generate creative solutions, deal with sophisticated relations and control them parametrically. It utilizes parameters to set relations between design elements in order to define a range of formal alternatives. It can also calculate algorithmic formulas and manipulate complex connections, besides creating sophisticated relations with several kinds of materials.

Andrade and Ruschel (2009) have identified that publications on the use of parametric modeling programs have emerged in the first decade of the 21st century in national congresses and events. Santana et al. (2015) infer that, although parameterization has been applied to energy efficiency studies for almost two decades in Brazil, the evaluations that take into account shape parameters are a novelty, due to the computational advances implemented in the 2010s.

2.3. Complex roof covers

According to Lebeé (2015), the concept of folding covers many significations. In nature, it can be related to specific shapes such as creases or pleats and may be found at different scales from the folding of graphen layers, to the unfolding of leaves and mountains (orogeny). "Pleated fabrics found on Egyptian frescoes prove that, long ago, mankind also handcrafted folds. However, the abstract idea of a folded surface emerged rather recently" (Lebeé, 2015, pp. 55).

When it concerns to the materialization of the parametric form, Pesenti et al. (2015) point out the kinematics potential of Origami creased patterns and investigate how those geometries can be modelled to optimize its surface displacements. Thus, the kinetics exploration is developed through the achievement of different ways to fold the surface.

"From Ori meaning 'folding', and kami meaning 'paper', the Origami, has evolved over the centuries from a traditional Japanese folk art to a design strategy for contemporary architecture and products" (Hemmerling, 2010, pp. 89). Origami is the art of folding, or more formally, "isometrically transforming, a sheet of paper into various forms without stretching, cutting, or gluing another piece of paper to it" (Tachi, 2010, pp. 203). Using origami, a complex 3D shape can be produced; hence, it can be applied for forming the shapes of a variety of architectural elements so that there is no need to assemble multiple parts.

Hemmerling (2010) states that the basics of the origami folds include valley and mountain folds, pleats, reverse folds, squash folds, and sinks. The number of basic folds is small, but they can be combined in a variety of ways to make intricate designs.

The use of Origami at different levels fits Origami patterns into several engineered applications; as deployable and reconfigurable structures, folding geometries have been used in biomedical devices, in space and aircraft applications. According to Pesenti et al. (2015), however, the use of self-folding Origami in architecture is mainly experimental, especially regarding shading devices and facade applications.

Since the form finding, geometry guides the project through the optimization of the shape, implementation of parameters, assembling circumstances and execution process.

Tachi (2010) strongly criticizes the fact that, when applying Origami to real life designs, it is important to control the customized 3D shape so that the resulting folded state is consistent with the required functionality, existing structures and environments. Therefore, according to Tachi (2010), computationally constructing an arbitrarily formed 3D surface using origami is a challenge to origami artists, architects, engineers, designers and personal users who apply origami to practical purposes.

According to Pesenti et al. (2015), a reason for choosing Origami as a process to develop shading screens is the spontaneous self-organization of these particular geometries, considered as an intuitive way to perform adaptation.

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In fact, thanks to tessellation's creases, the Origami folding patterns enable the system to deform easily into a preset deformation direction, while remaining stiff in the other directions. These systems are capable of changing their shape to accommodate new requirements while maintaining a continuous external surface, as quoted by Peraza-Hernandez et al. (2014).

There is a deep connection between origami and mathematics, which has given rise to a new theoretical field of research in recent decades, called origami mathematics. Lebeé (2015) states that origami provides more possibilities than the classical Euclid axioms, since trisecting an angle is not possible with rule and compass, but can be done with folding.

Hemmerling (2010) also states that a considerable amount of mathematical study has focused on the art of Origami, since it is related to geometric principles. "The knowledge of geometric rules is at the same time an essential condition for the development of architecture in the design as well as in the realization process." (Hemmerling, 2010, pp. 90).

As reported by Lebeé (2015), rigid folding is the most used and researched pleat. It happens when all the deformation is focused on the hinges, while the faces between the pleats remain flat. The curved folds are a more general class of pleats. In this case, the fold line is not straight. This rather simple generalization of folds actually generates a much more complex understanding of folding. Clearly, the surface is no more rigid-foldable.

Since folding is certainly the most simple and inexpensive process for transforming matter, it is a good starting point for design. Its process enables fast and easy achievement of three-dimensional shapes, which shows better structural properties than the original sheet and directly defines an envelope, separating the "inside" from the "outside".

According to Peraza-Hernandez et al. (2014),

> In the mid-1970s, mathematicians discovered that an endless number of shapes could, in theory, be created using traditional origami (initially planar shape, only folds allowed). These discoveries enabled new approaches for manufacturing, assembling, and morphing of devices and structures based on origami principles. This is evident in the increasing attention mathematicians, scientists, and engineers have given to origami theories and tools over the past four decades. (Peraza-Hernandez et al., 2014, para. 2)

Peraza-Hernandez et al. (2014) state that Origami offers designers novel ways to fabricate, assemble, store, and morph structures. Potential advantages include the ability to compactly store structures, reconfigure structures and reduce manufacturing complexity. It provides a quick response to the urgent request of building a structure. It is viable to create an outer skin or a canopy in a single operation, using pre-fabricated structures, working directly in a whole structure, rather than in every single element, which reduces assembly time. It even gives immediate structural logic, and all the pieces are linked to each other (Mattoccia et al., 2016).

Today, the combination of parametric tools, new fabrication and prototyping processes based on numerical control and 3D printers brings architects and designers even closer to actual constructions.

Three patterns are particularly interesting: Yoshimura pattern, Miura Ori pattern and Diagonal pattern. All three are based on a combination of simple accordion folding and reverse fold, which means that they are a series of straight valley and mountain folds bent in the reverse folds to form simple curved surfaces (Fig. 1).

According to Lebeé (2015), Miura Buckling is the most investigated pattern. The homogenized behavior of the pattern alone was studied, as well as its behavior when used as the core of a sandwich panel. Many generalizations of the pattern were suggested, which are under current investigation.

According to Gilewskia et al. (2014), folded plates[1] are also an attractive solution for architects and there are a lot of interesting engineering structures of this kind. Considering its aesthetic results, along with its easy generation through parametric modeling tools, it is believed that this type of geometry of Origami engineered structures will be increasingly used in contemporary buildings, which justifies its study.

2.3.1. Yoshimura pattern (diamond pattern)

According to Hoff (1966), this buckling pattern is named after Yoshimaru Yoshimura, the Japanese researcher who first provided an explanation for its development in a paper published it in Japan in 1951, and later republished in the United States.

The basis of this pattern (Fig. 2) is a diamond shape, fold in one of its diagonals. In the Figure, blue lines represent mountains and red dotted lines represent valleys. The Japanese scientist observed that thin walled cylinders show this kind of buckling pattern under axial compression (Buri and Weinand, 2008; Hunt and Ario, 2005). This pattern (also referred to as the diamond pattern) is constructed by repeating a single 6-degree vertex with mirror symmetry.

Another variation of this pattern can be obtained by splitting the diamond, or kite shape, and stretching it along the folded diagonal. The result is a hexagonal pattern formed by symmetrical trapezoids.

The diagonals of the diamond are equivalent to the main crease of the reverse fold and the edges of the diamond to the side creases. The curve of the folded pattern is designed by the shape of the diamonds. "The acuter the angle α between the diagonal of the diamond and its edge, the flatter the bending of the pattern." (Buri and Weinand, 2008, para. 6).

According to Chudoba et al. (2014), the Yoshimura crease pattern takes on shapes with a single curvature at any intermediate stage of folding. The shapes achieved in this form are well known in architecture. They are assembled using triangular elements of the same size.

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[1] "From mechanical point of view the correct theory to describe folded plates is six parameter shell theory with three displacements and three rotations in the displacement field. The third rotation is necessary because of folding the structure. Each fold is flat, so the equations of the theory can be simplified." (Gilewski et al., 2014, pp. 220) They are assemblies of flat plates, rigidly connected along their edges in a way that the structural system is capable of carrying loads without the need for additional supporting beams.

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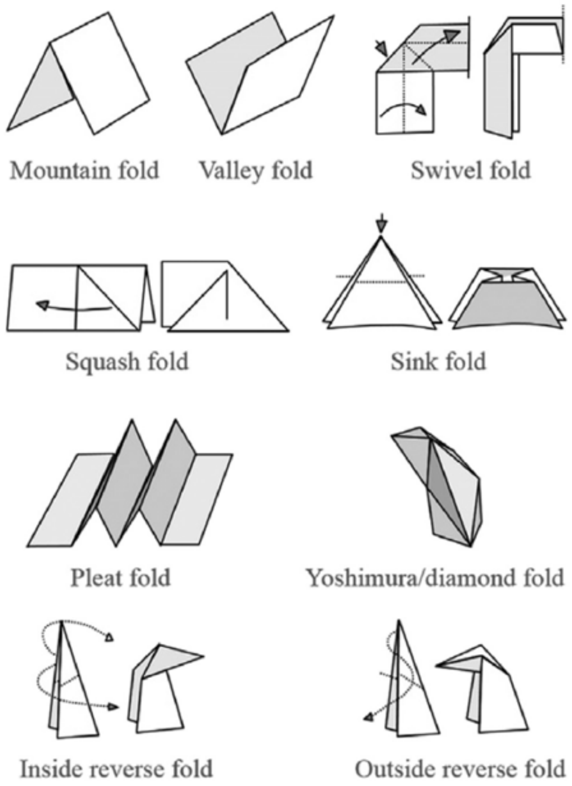

Fig. 1 Basic origami folds and techniques. Source: Redrawn from Gilewskia et al. (2014).

The individual facets remain rigid when the buckling is not folded proportionally and are not imposed to any deformation at any stage of the folding process.

Chudoba et al. (2014) also state that its global curvature can be varied by changing the relation between the crease line length in both directions and by scaling the Yoshimura elements, so that their sides have different lengths.

2.3.2. Diagonal pattern

According to Buri and Weinand (2008), the basis of this pattern is a parallelogram folded in its diagonal, (Fig. 3), where the blue lines represent mountains and the red dotted lines represent valleys. Out of a parallel position, the edges are turned up diagonally. A series of folded parallelograms form a helical distorted folding. "A similar buckling pattern appears when a thin walled cylinder shell is compressed with a distortion" (Buri and Weinand, 2008, para. 7).

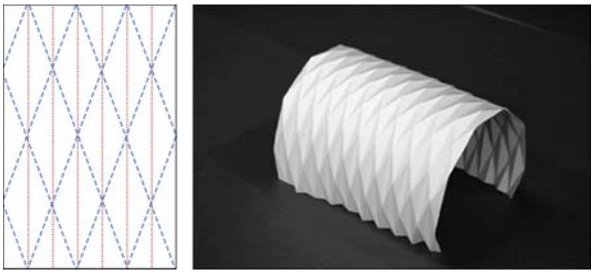

Fig. 2 Yoshimura buckling. Source: The author; Buri and Weinand (2008).

According to Buri and Weinand (2008), the Diagonal and the Yoshimura "mainly differ by the fact that valley folds of diamond pattern form a plane polygonal line whereas the valley folds of the diamond pattern form a helical polygonal line" (Buri and Weinand, 2008, para. 7).

2.3.3. Miura Ori pattern

According to Nishiyama (2012), the Miura fold (Fig. 4), is a method of folding named after its inventor, Japanese astrophysicist Koryo Miura.

Bain (1980) states that the crease patterns of the Miura fold form a tessellation of the surface by using parallelograms. In one direction, the creases lie along straight lines, with each parallelogram forming the mirror reflection of its neighbor across each crease. In the other direction, the creases zigzag. "Each of the zigzag paths of creases consists solely of mountain folds or of valley folds, with mountains alternating with valleys from one zigzag path to the next." (Bain, 1980).

Nishiyama (2012) says that this fold is a form of rigid Origami, which means that it can be carried out by a continuous motion in which, at each step, each parallelogram is completely flat. This property allows it to fold surfaces made of rigid materials.

According to Miura (1985), this pattern was employed due to its ability to be used in the construction of solar sails for satellites that could be packed in a very compact way and have maximum extension when unfolded (Buri and Weinand, 2008). The pattern is composed of symmetric trapezoids that form a herringbone tessellation.

3. Research methodology

3.1. Form selection

Taking into consideration the applications of the Miura Ori Tessellation form, altogether with its adaptability and freestanding characteristics, this was the pattern chosen for the construction of the parametric form. Among the patterns presented, the Miura-Ori pattern was selected due to its rigidity, easy motion and freestanding characteristics. The folded pattern has a zigzag feature in two directions, which allows extending and retracting the pattern in both directions.

Any thin horizontal surface can cover a large span, but will bend under its dead weight. The folds give the surface the resistance to support loads. Each inclined face of the folded surface functions as a beam, which is horizontally supported by the adjoining face.

3.2. Form parameterization

According to Buri and Weinand (2008), the form of parallel corrugations can be manifold. Extension is the main parameter characterizing a series of parallel folds. It can define the direction and magnitude of the deploying creases. The either chosen direction can be straight, bent or

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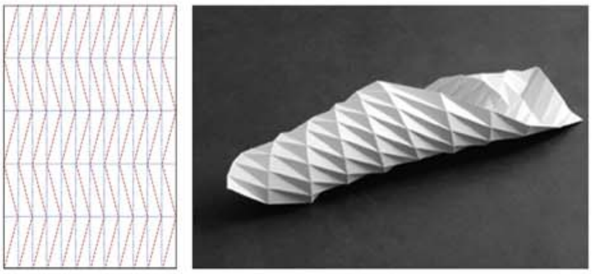

Fig. 3 Diagonal buckling. Source: The author; Buri and Weinand (2008).

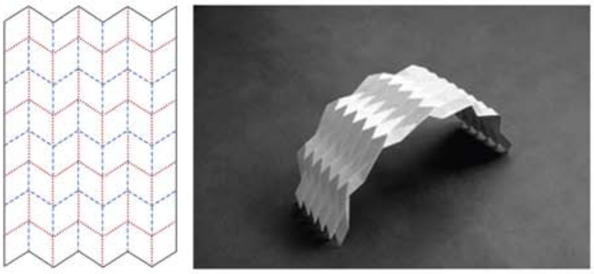

Fig. 4 Miura Ori buckling. Source: The author; Buri and Weinand (2008).

take an arbitrary curvilinear or polygonal form. The magnitude may vary between an entirely closed and a completely opened state. Extension length and amplitude vary according to the chosen magnitude. Other typical variation is the amplitude constant growth or reduction. Local or general variations of amplitude can be used to adapt the folded plate structures to stress. The higher the amplitude, the stronger the resistance of the folded plate structure. The order of mountain and valley folds does also qualify the appearance of a series of parallel folds.

The most basic folding is a corrugation of parallel mountain and valley folds. It can be described as an extrusion of a zigzag line along a straight line. The zigzag is characterized by the extension and the amplitude of its segments.

Using the Rhinoceros3D® and Grasshopper® parametric modeling suite, a solar protection element using Miura-Ori Buckling pattern was created.

This choice is based on the idea of exploring the potential of the modeling tools, besides investigating the behavior of complex surfaces[2] applied as shading device.

In order to establish the cause and effect relationships between the geometry and performance of the developed shading elements, the following geometric parameters of variation between the models were defined: Number of Modules, Scaling of Modules, Deviation or Angulation and Aperture.

In order to obtain a foldable surface, the methodology used was extracted from Mattoccia et al. (2016). The main steps of the algorithm (Fig. 5) are listed below:

(1) Defining a starting point A;
(2) Defining a line AB, giving the starting point A, its length and the azimuth angle A'AB;
(3) Defining a second line BC giving the starting point B, its length and two angles, the vertical one B''BC and the horizontal one B'BC;
(4) Defining the first starting plane ABCD, giving the two previous lines and the inner angle BCD;
(5) Defining a third line giving the starting point B, its length and the vertical angle B''BE;
(6) Defining the second starting plane BCFE, giving the line BC and BE and the inner angle BCF;
(7) Find the other two planes of the smallest constituent component CDHI and CHGF using the relation about the dihedral fold angles which are related to the previous inner angles BCD and BCF;
(8) The last step, according to Mattoccia et al. (2016) is to continue the surface in the transverse direction, getting the two new planes EFML and MFGN.

Having the object divided into planes allows resizing of the module at any time, as well as increasing the number of modules in the *X* or *Y*-axis (Fig. 6).

As it can be seen, 3 Number Sliders are responsible for the scale of the model. The *X* Length one is responsible for scaling the module in the *X*-axes. Deviation, despite being connected to the *Y*-axes, is responsible for the angulation and deviation in the *Y*-axes, making the model angles more or less acute.

The *Y* Length, on the other hand, is responsible for scaling in the *Y*-axes. There is also an *X* and *Y* count controlling the number of modules in each axis.

The main module was constructed in the *XY* plane (Fig. 7) and an original folding asset is created and maintained at 100 to prevent deformity. A folding asset is created to simulate the plate foldability. It ranges from 0.00 to 0.99, so that 0.00 is a flat surface, with no buckling, and 0.99 is the Miura fold completely folded and retracted.

3.3. Factorial analysis for radiation output

According to Montgomery et al. (2012), the Factorial Analysis is an alternative to discover interactions between the variables. Experimental planning is a technique based on defined scientific and statistical criteria, with the purpose of determining the effect of the variables on the results of a given process.

According to Ferreira (2016), in the Factorial Analysis, all factors[3] are varied together. The number of factors

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[2] According to Paoletti (2006, our translation), complex surfaces are those that appear as fluid, formed by spherical solids in order to create curved volumes or volumes with complexity in their morphology and material, maintaining close relation with information technologies and, above all, with junction of a great number of responsibilities and competences, aiming to organize the constructive processes.

[3] Linear combination of the original variables, forming statistical variables to maximize their power, in order to explain the complete set of variables (Hair et al., 2005).

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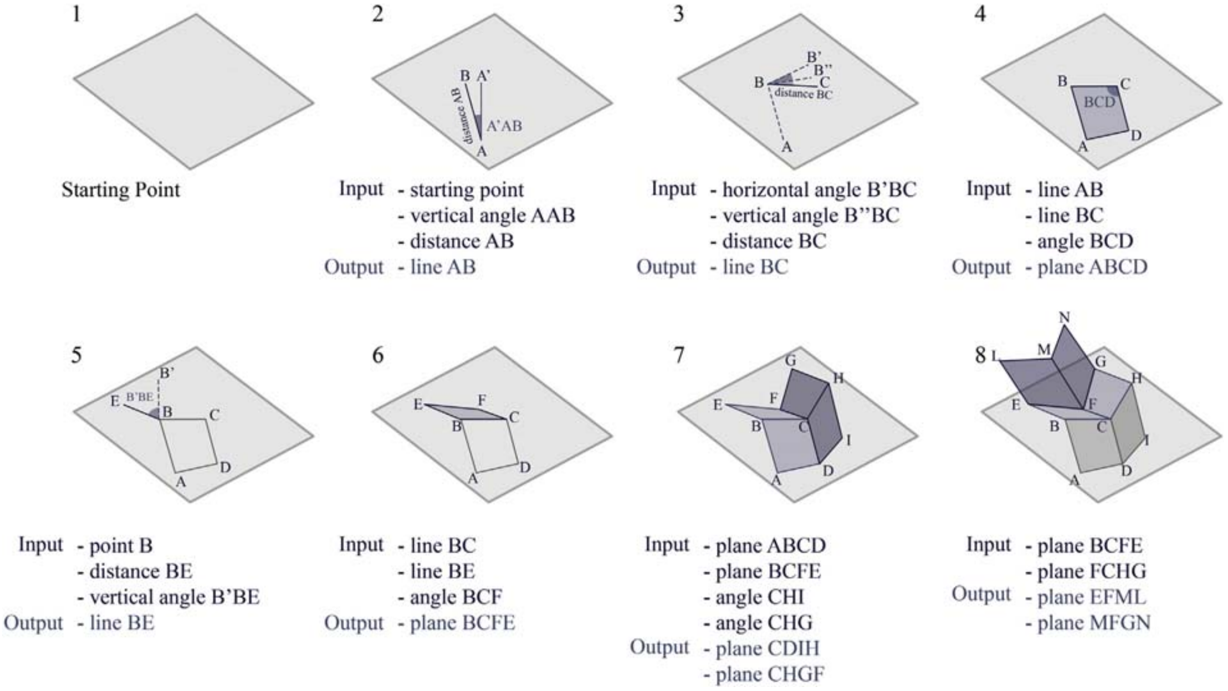

Fig. 5 Steps followed in Grasshopper. Source: Mattoccia et al. (2016).

will depend on the number of variables and levels of experimentation. The simplest type is factorial, 2k. The terminology derives from the fact that only two levels for each factor k are assumed. One indicates the low level, represented by a minus (−) and the high level, represented by a plus (+), or indicates the presence or absence of a factor. Besides, each factor level combination can be tested more than once in order to minimize the effect of random errors, which is called replica (Reddy, 2011).

The replica is usually applied in experiments with many factors or a lot of information to process. To avoid making the experiment impracticable due to its size, it is run at two levels at maximum, according to Pinto (2003). Montgomery et al. (2012) state that there are no restrictions regarding the amount of factors and levels that a factorial design may contain. The factorial experiments adopted were two levels for cardinal orientations and collateral orientations (Tables 1 and 2). The simulation outputs of Annual Average of Hourly Radiation were used in the Factorial Analysis.

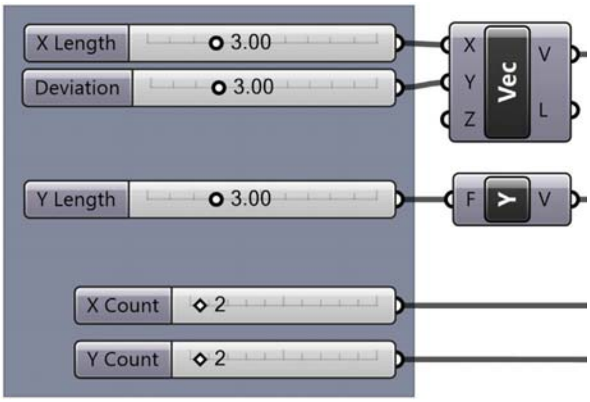
X Length 3.00
Deviation 3.00
Y Length 3.00
X Count 2
Y Count 2

Fig. 6 Input parameters for canopy and modules size. Source: The author.

The effect of each variable on the process is delimited by means of controlled changes in the process and evaluation of the impact on the results, or the output data, obtained in the interactions. We use the Variance Analysis (ANOVA) techniques to identify statistically robust models with good performance between the response variable and the various factors. The analysis of variance allows evaluating the degree of reliability of the measures obtained, that is, if the effects are significantly different from zero. In particular, ANOVA tests whether several populations have the same mean by comparing the dispersion of the sample means with the variation within the samples (Montgomery et al., 2012).

For this study, the factorial analysis was applied to determine the most sensitive parameters applied to the canopy.

From the experiments, the simulations and their corresponding outputs are defined and used as output variables of the factorial analysis, which will be later statistically treated by analysis of variance (ANOVA).

After the definition of the levels of the parameters and the output variable, the factorial experiment was elaborated and the simulations were run to obtain the Annual Average of Hourly Radiation, used as the main output variable.

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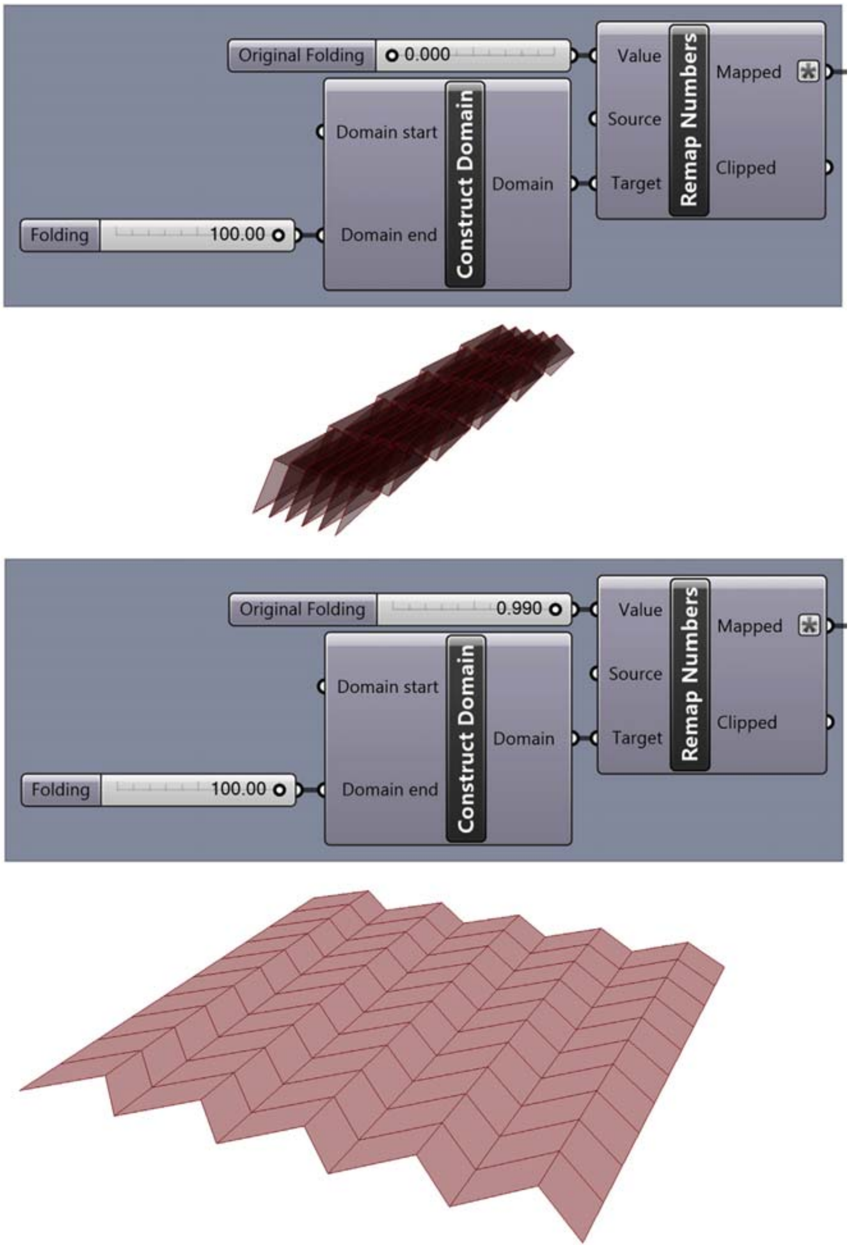

Fig. 7 Parameters for Folding and their impact on the Canopy. Source: The author.

3.4. Simulation

The plug-in LadyBug® for Grasshopper® was selected for radiation analysis, Operative Temperature (To) and Percentage of Time in Comfort (PTC), since, according to Roudsari and Pak (2013), Ladybug® imports standard EnergyPlus Weather files (.epw) into Grasshopper® plug-in and provides a variety of 2D and 3D interactive graphics to support the decision-making process during all stages of design. It also simplifies the process of analysis, automates and expedites the calculations and makes it easy to understand and manipulate graphical visualizations in the 3D modeling interface of Rhino/Grasshopper®. "It also allows users to work with validated energy and daylighting engines such as EnergyPlus, Radiance and Daysim" (Roudsari and Pak, 2013, pp. 3129).

The plug-in HoneyBee® for Grasshopper® was used for ASHRAE Adaptive Comfort Calculations. According to Roudsari and Pak (2013), Honeybee® is an extension of Ladybug® that increases the ability to work with Radiance, Daysim or EnergyPlus. "Similar to Ladybug®, Honeybee® is designed to run the analysis on building masses but for more advanced [lighting] studies" (Roudsari and Pak, 2013, pp. 3132).

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Considering the need to measure the levels of Total Radiation and obtain the Annual Average of Hourly Radiation, a plan needs to be created just below the structure of the Canopy. The plane created below the canopy should be smaller than the Canopy so as to be affected by the shadows cast by the object and collect the least amount of solar radiation unaffected by the canopy. Following the methodology applied by Cartana et al. (2018) for radiation simulation, the horizontal plan was created 10 cm aloof from the canopy alignment, with sensors spaced by 20 cm × 20 cm.

In this stage, the Radiation analysis plan just below the structure will be used as the main assessed geometry while the Canopy will be inserted separately as a context geometry.

The simulation was performed for a full year using the weather file TMY3 (Guimarães, 2016) for Viçosa, MG (Latitude 20° 45′14″S, Longitude 42° 52′ 55″ W, Altitude 648 m). Since the canopy is parameterized, the simulations work adequately for any other place, with different solar radiation, depending only on the weather file inserted.

The canopy was chosen because in places with hot and humid climates, such as Brazil, the roofing areas are critical parts of the building envelopes and "highly susceptible to solar radiation and other environmental changes, thereby, influencing the indoor comfort conditions for the occupants" (Sadineni et al., 2011, pp. 3622).

4. Analysis

4.1. ASHRAE 55 adaptive comfort and Percentage of Time in Comfort (PTC)

According to Lamberts et al. (2013),

> since there was no Brazilian thermal comfort standard available for workplaces, studies carried out during the 1990's and 2000's were vastly influenced by the ISO 7730's procedures, which is based on Fanger's [predicted mean vote/predicted percentage of dissatisfied] PMV/PPD equation. (Lamberts et al., 2013, pp. 19)

Lamberts et al. (2013) discuss that, although studies were affected by ISO 7730, the few research works attempting to establish thermal comfort zones across different climatic zones in Brazil revealed significant differences regarding the percentage of people dissatisfied with the use of Fanger's PPD, particularly in hot and humid climates. This is observed mainly because "occupants in naturally ventilated buildings accept temperature swings during the day and year, and prefer higher air velocities if controls and fans are provided." (Lamberts et al., 2013, pp. 22).

Table 1 Levels for the cardinal factorial experiment.

Factor Level	Factor A	Factor B
	Cardinal Rotation	Slope
Low (−)	South	5°
High (+)	North	20°

Factor	A	B	Description
(1)	−	−	South 5°
A	+	−	North 5°
B	−	+	South 20°
Ab	+	+	North 20°

Table 2 Levels for the collateral factorial experiment.

Factor Level	Factor A	Factor B	Factor C
	Cardinal Rotation	Collateral Rotation	Slope
Low (−)	South	West	5°
High (+)	North	East	20°

Factor	A	B	C	Description
(1)	−	−	−	Southwest 5°
a	+	−	−	Northwest 5°
b	−	+	−	Southeast 5°
c	−	−	−	Southwest 20°
ab	+	+	−	Northeast 5°
ac	+	−	+	Northwest 20°
bc	−	+	+	Southeast 20°
abc	+	+	+	Northeast 20°

In this scenario, the latest version of ASHRAE Standard 55 (2013) "emerges as the best inspiration for any thermal comfort standard worldwide" (Lamberts et al., 2013, pp. 24). The Standard defines acceptability limits of 80% comfort for typical applications and 90% comfort when a higher standard of thermal comfort is desired. It indicates the percentage of occupants expected to be comfortable at the indicated indoor and prevailing mean outdoor temperatures (Table 3).

According to de Dear and Brager (1998), the adaptive comfort adopts varying internal temperature standards and allows users to adapt to the environmental conditions of the building. This approach leads to more responsive environmental control algorithms, improved levels of occupant comfort and reduced energy consumption, besides promoting sustainable projects.

The adaptive comfort considers the human body as an active agent that interacts with the environment in response to its preference and thermal sensation. It is based on a broad sampling of field studies conducted in various parts of the world, whose indexes are based on results that measure environmental conditions and the simultaneous response to thermal sensation in individuals involved in their usual tasks (de Dear and Brager, 1998). The researches seek to reproduce the real conditions, where the users of the building are active agents in the thermal conditions of the environment. Besides, the populations of different climatic regions, socio-cultural and

Table 3 Acceptability and applicability ranges of adaptive comfort model. Source: ASHRAE 55 2013 Standards.

Acceptability Limits	Air Velocity (m/s)	Activity level (met)	Clothing Insulation (clo)	Operative Temperature (°C)	
				Summer	Winter
80%	<0.2	1.0–1.3	0.5–1.0	30.3	23.3
90%	<0.2	1.0–1.3	0.5–1.0	24.3	24.3

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socioeconomic contexts have different perceptions of comfort, as reported by Pereira and Assis (2010).

The thermal performance of the space can be evaluated using Total Comfortable Hours (TCH) followed by Percentage of Time in Comfort (PTC), Percentage Hot (PH), Percentage Cold (PC), and Adaptive Comfort (AC) (also called condition of person), where the input conditions are: −1 cold; 0 comfortable; +1 hot for occupants.

According to Abdullah and Alibaba (2018), Ladybug Adaptive Comfort Calculator measures TCH, PTC, PH, PC, and AC values, whereas an adaptive comfort chart can be generated using the Ladybug Adaptive Comfort Chart.

ASHRAE 55 Adaptive comfort is applicable for the determination of the comfort indices in naturally ventilated environments, where the physical activity of users is between 1.0 met and 1.3 met. The method also specifies that occupants can freely adapt their clothing to internal and/or external thermal conditions within a range of 0.5–1.0 clo and an average air temperature between 10 °C and 33,5 °C is adopted (ASHRAE, 2013). The standard also determines that the acceptance limit range for typical construction applications must satisfy 80% of the individuals.

4.2. Operative temperature (To)

ASHRAE 55 (2013) Standard defines operative temperature as the weighted average of Mean Radiant Temperature (MRT) and air temperature, since occupants tend to lose half of their body heat through radiation and the other half by air-related factors, such as air temperature and humidity. It is a primary metric by which adaptive comfort and thermal conditions are measured.

4.3. Thermal Comfort Percent (TCP)

According to Abdullah and Alibaba (2018), "Thermal Comfort Percent, as a metric to map spatial comfort, is the percentage of time where a given point in space appears inside the adaptive comfort range" (Abdullah and Alibaba, 2018, para. 20).

TCP can be interpreted as a loss in comfortable hours and in comfortable space in the analyzed period.

5. Results

5.1. Factorial analysis

Initially, the input values obtained after simulation for radiation in Grasshopper® are presented for the canopy, taking into account the cardinal directions. The effects calculated by Minitab for each of the factors are presented in Fig. 8 along with 10 replicas, each one relative to 36 days of the year. The output variable in this analysis is Annual Average of Hourly Radiation.

For this factorial configuration, 3 types of replica were tested. The first test presented 4 replicas, one for each season. The second presented 6 replicas, each one with 2 months. The 10-replica configuration produced a more robust model, with less error and did not compromise the simulation time, taking into account that in a 2-level factorial, the number of tests is equivalent to 2^k multiplied by the number of replicas, where k is the number of factors.

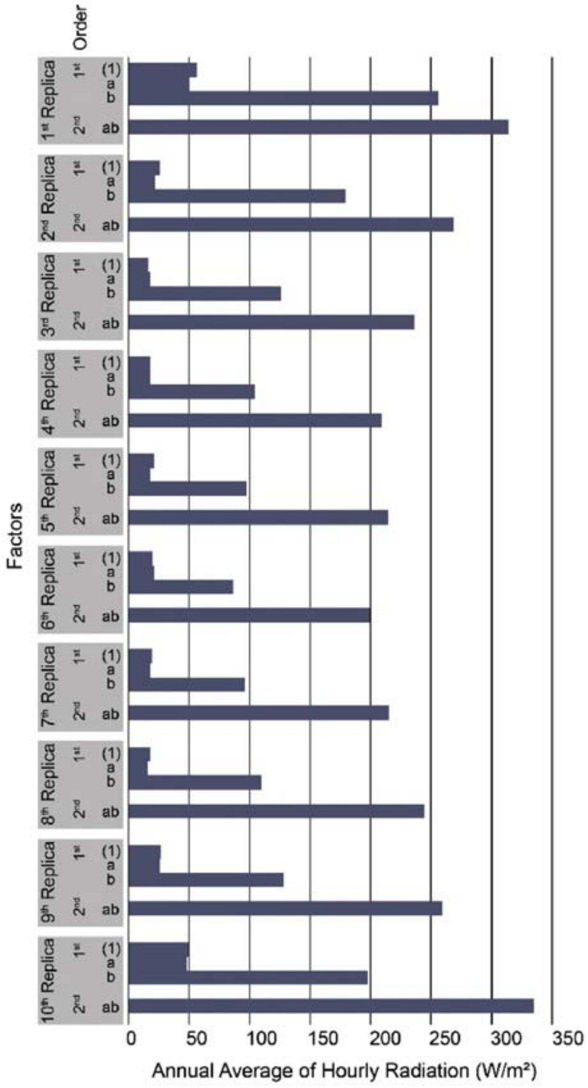

Fig. 8 Factors for factorial analysis and replicas for cardinal directions. Source: The author.

For the Cardinal Analysis, the number of radiation simulations run was 40 (Fig. 8). It is observed that the level of Annual Average of Hourly Radiation is lower for Factors of the first order, more specifically for (1), which refers to

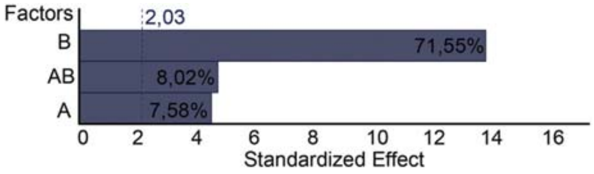

Fig. 9 Pareto chart of the standardized effect for cardinal directions. Source: The author.

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south 5°, and A, north 5°. It indicates lower levels of radiation for the plan below the canopy when it is less steep and little dependant on orientation.

The analysis of the output data obtained by simulation (Fig. 9) reveals that the cardinal direction alone is among the factors that least affect the model.

Factor a (cardinal rotation) contributed with 7.58%. However, the linear factor can still be considered interesting, even if it is lower than factor b, related to the slope of the canopy, which contributed with 71.55%, as well as the two-way interaction factor ab, related to the combination of factors (cardinal rotation and slope). Then, it can be concluded that the effect was representative for the case analyzed. Minitab shows a Model contribution of 87.15%.This indicates the occurrence of a 12.85% error embedded, which is acceptable. This error may indicate the existence of another important variable that has not been analyzed.

In a normal probability plot, the sorted data are plotted vs. values selected to make the resulting image look close to a straight line. Deviations from a straight line suggest departures from normality. The data distribution analysis (Figs. 10 and 11) shows that they follow such behavior, despite a slight deviation.

Normal distribution can also be analyzed by means of a histogram, which is an accurate representation of the distribution of numerical data. It is an estimate of the probability distribution of a continuous variable. The intervals must be adjacent. They often present the same size when the distribution is uniform. The histogram obtained through simulation for cardinal directions shows good normal distribution for the factorial experiment (Fig. 11), with slight deviation for positive values but roughly symmetric.

If the data distribution is not normal, or close to the normal, the effect calculation is a mean between the output variables obtained for the positive factors and negative factors. Thus, the means are no longer representative, but rather corrupted and tending to the stronger variables.

A 2-level factorial with 3 factors was created for the Collateral directions. The number of replicas remained the same, 10 replicas relative to 36 days for each year. Eighty radiation simulations were run.

The Factors graph (Fig. 12) shows the first replica, or the first 8 simulation results. In this experiment, it is observed

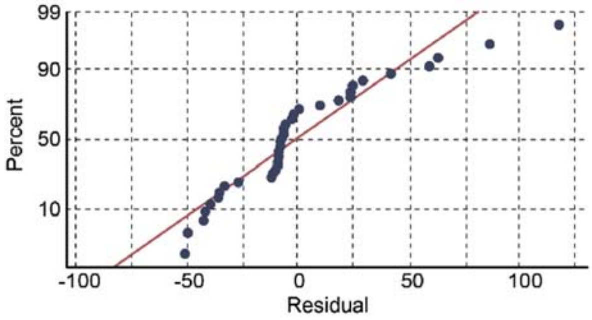

Fig. 10 Normal probability plot for cardinal directions. Source: The author.

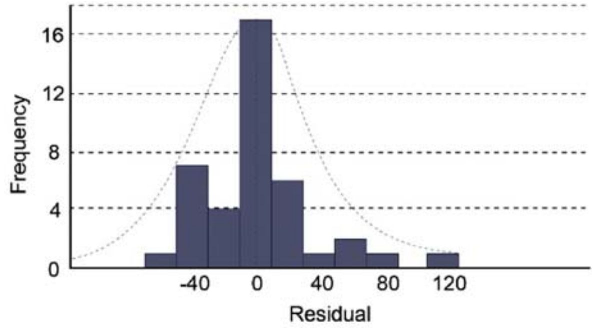

Fig. 11 Histogram for distribution of Normal for Cardinal Directions. Source: The author.

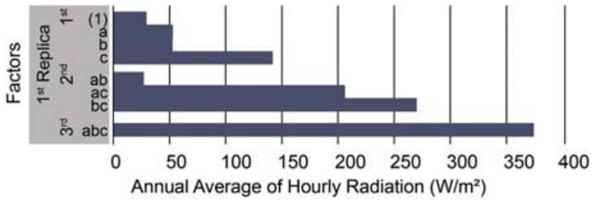

Fig. 12 Factors for factorial analysis for collateral directions. Source: The author.

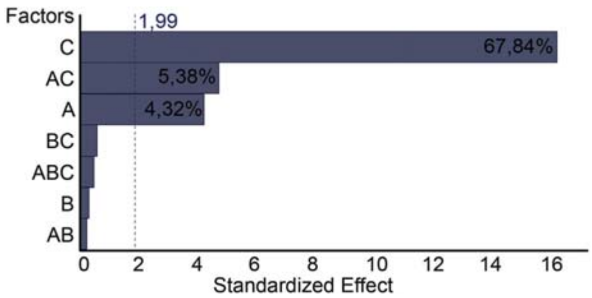

Fig. 13 Pareto chart of the standardized effect for collateral directions. Source: The author.

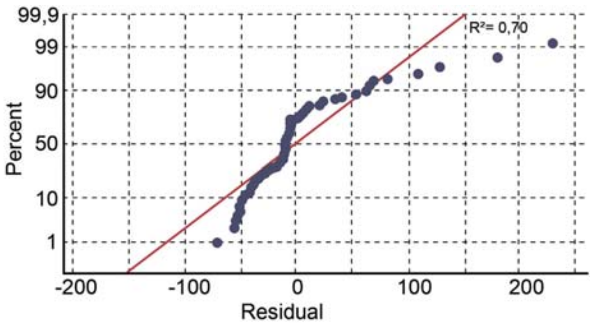

Fig. 14 Normal probability plot for collateral directions. Source: The author.

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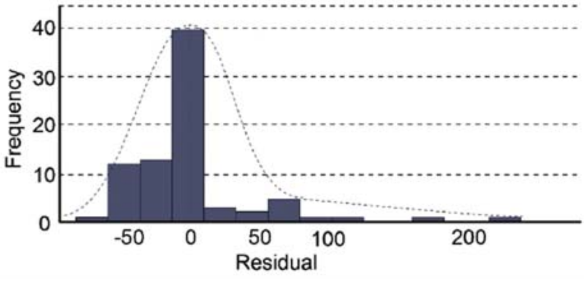

Fig. 15 Histogram for distribution of Normal for Collateral Directions. Source: The author.

that the level of Annual Average of Hourly Radiation for Factors of the first order is higher than those in the first experiment. However, the collateral and cardinal directions provided similar contributions. Factors of second and third order present even higher levels of Annual Average of Hourly Radiation, but only when combined with factor c, responsible for the slope.

The Pareto Chart for this factorial Analysis (Fig. 13) shows that factor c (slope) has the highest contribution, 67.84%. The correlation between the collateral direction represented by a and the slope represented by c is also an interesting two-way factor combination, which accounts for 5.38% of contribution to the factorial. Alone, a accounts for 4.32% of contribution, once the factor related to the slope had space to connect with other factors and increase its contribution proportionally. Minitab shows a Model contribution of 77.63%. This reveals a 22.37% error embedded, which is acceptable.

The highest error embedded in the model transmitted to the normal analysis. In the Normal Probability Plot (Fig. 14), it is observed a detachment from the normal, more pronounced than in the previous experiment.

This can be seen in the histogram (Fig. 15), which shows that the Normal is displaced, tending to the stronger values. The histogram presents two Outliers, which is an extremely high value that does not fall near any other data points. This can represent unusual cases, data entry errors, or perhaps data that do not belong to other data of interest. For this analysis, the residual values are left-skewed and the mean may not provide a good estimate for the center of the data and represent where most of the data fall. In this case, the mean is typically less than the median.

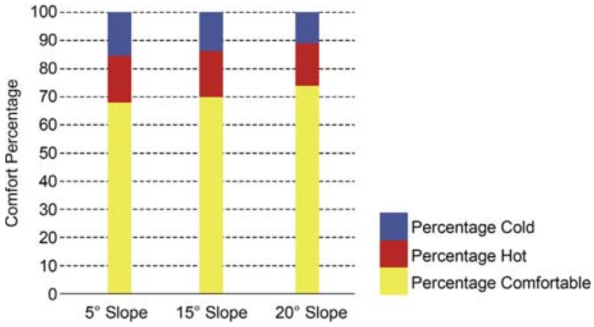

Fig. 17 Comfort percentage according to parameter change. Source: The author.

5.2. Simulation analysis

As observed in the Factorial Analysis, the slope was the most robust factor analyzed and generated a higher level of differentiation between the radiation levels. Therefore, the North orientation was fixated for the model analyses and 3 different slopes were analyzed, 5°, 15° and 20°. The first is relative to a small slope on the canopy, only for water drainage. The second is relative to the equivalent angle for the minimum slope adopted in Brazil, which is 25%. The last one is an angle equivalent to the typical slope adopted in Brazil for ceramic roof tiles, which is between 30% and 38%.

5.2.1. ASHRAE 55 adaptive comfort and Percentage of Time in Comfort (PTC)

For the creation of the ASHRAE Adaptive Comfort for the Whole Year (Figs. 16 and 17), the space below the canopy was treated as one zone in HoneyBee®. For the zone Programming, it was treated as a natural ventilated hallway with fenestrations of 70% facing North and South and 50% facing East and West.

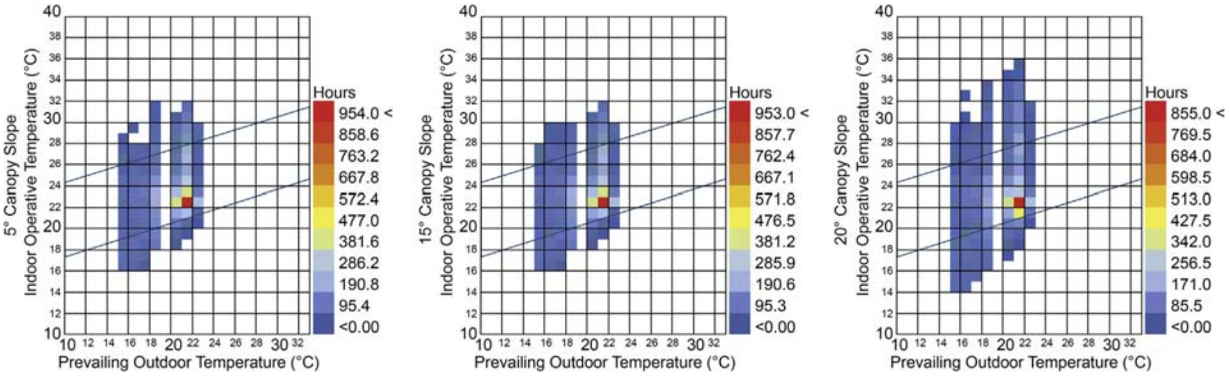

Fig. 16 Adaptive comfort chart for ASHRAE 55. Source: The author.

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The adaptive comfort chart in Fig. 16 demonstrates the boundary of the comfort range for the 80% acceptability limit stated by the ASHRAE 55 standard.

This method defines a correlation between indoor operative temperature and prevailing outdoor temperature and explains that residents accept warmer degrees when outdoor air temperature rises. "The colorful squares represent the available comfort hours. for which the saturated colors in red contain a higher number of desired hours" (Abdullah and Alibaba, 2018, para. 29). The blue edged polygon indicates the adaptive comfort range.

The microclimate map visualizations show a significant thermal quality towards more comfortable space indoors and fulfil the intended acceptability limit of 80% for the ASHRAE (2013) Standards for 5°, 15° and primarily for 20°. The operative temperature was very close to the ideal degree almost at all points for most of the time when the analysis is carried out in percentage and the maximum shift is of 5 °C up and 3 °C down for the overall temperature for a natural conditioned space.

The thermal performance was evaluated using the adaptive comfort model (Fig. 16). The results showed that the total comfortable hours (TCH) were 5931 h, out of the 8760 simulated hours, in a year, for 5° slope. This number indicates that, in 67.7% of the total hours, the space was comfortable, corresponding to 32.3% of time in discomfort (PTD) (Fig. 18). The discomfort hours happened mainly between May and August, relative to fall and winter respectively, and predominantly before 8 AM. A critical comfort percentage was detected during the summer, mainly in March and the beginning of April, relative to fall.

The representation of Canopy slope of 15° was similar to that of 5°. Despite the visual representation, the data showed a TCH of 6132 h out of the 8760 simulated hours. This indicates a 70.0% of total comfort hours and corresponds to 30.0% PTD.

The results for 20° showed improvement when compared to the other slopes, as observed in Figs. 17 and 18. The simulation shows the percentage of 74.0% of comfortable hours, which accounts for a TCH of 6482 h out of the 8760 simulated hours and a PTD of 26.0%. The discomfort reported during the fall and winter (from March to September) is minimized and, besides the hours of discomfort in the middle of the year, due to cold, there is a small concentration of discomfort hours in the end of the summer (from December to March).

The ASHRAE Condition of a Person (Fig. 18) shows values for comfort or lack of comfort. Values of −1, for instance, are acknowledged to be cold and values of +1, hot. For 5° Canopy Slope, the Adaptive Comfort Calculation also indicates a percentage of 67.7% of comfortable time when dealing with inner spaces, with 16.7% PH and 15.5% PC, as observed in Fig. 17. For 15°, the simulation shows results of 16.2% PH and 13.8% PC. The best results were shown for 20°, with 15.4% PH and 10.6% PC.

5.2.2. Outdoor Shade Benefit

The Shade Benefit Chart for the whole year (Fig. 19) shows the benefit of shading with and without the 20° slope canopy application. As observed, the analysis of the shaded space reveals that the thermal condition of the space remains approximately within the adaptive comfort range of 25 °C, which is the lowest bound between 6AM and 6PM, during summer, and of 30 °C, which is the highest bound for the same time during the summer, based on the 80% acceptability limit of the ASHRAE 55 (2013) Standard. For the winter, the highest bound was 25 °C, which is within the adaptive range. The lowest bound was reported before 6AM, when the space is underused. Considering temperatures after 8 AM, the lowest bound reached 17 °C in June and July, which are winter months in Brazil. The results for 5° and 15° were very similar to those presented for the 20° slope.

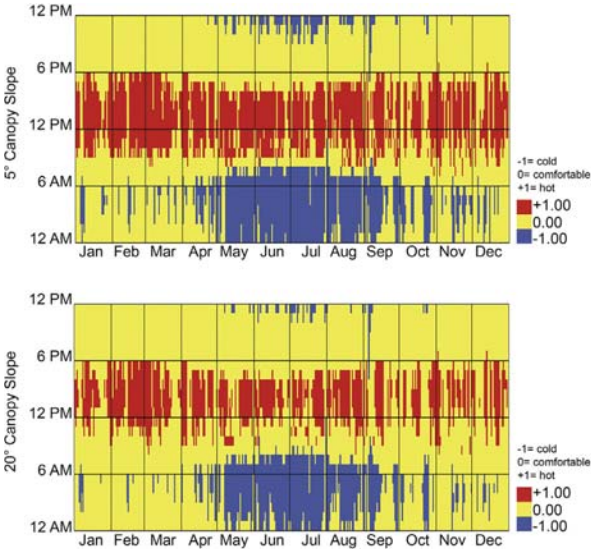

Fig. 18 ASHRAE 55 condition of a person. Source: The author.

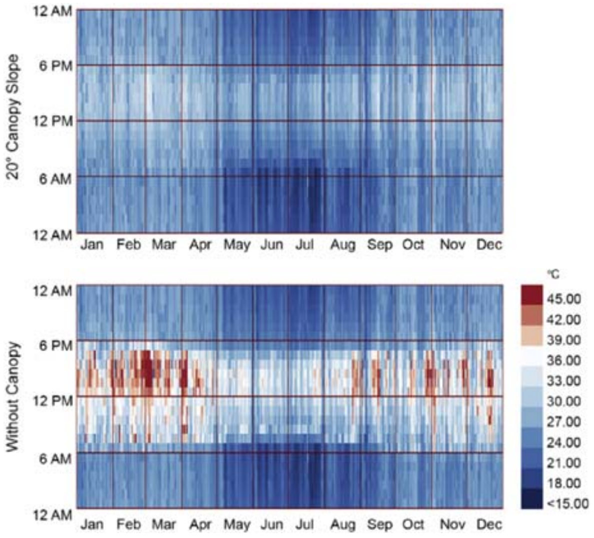

Fig. 19 Outdoor Shade Benefit for the whole year. Source: The author.

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In the analysis of the space without the canopy, the temperature reached 45 °C in March and was consistently high throughout the summer months, from December to March. The temperature decreased slightly between May and August, relative to Fall and Winter, respectively. However, it was still higher than the range of Tcomf ±2.5 °C for 80% Acceptability Limits during summer and winter.

The discomfort cold hours were mostly reported during the nighttime and before 6 AM, which did not noticeably affect the simulated analysis hours (08:00—18:00). However, due to the adiabatic walls adopted for the simulated model, which eliminates internal heat flows between the possible zones, the night times seemed colder than they actually were.

6. Conclusions

This study used parameterization, simulation and factorial analysis tools applied to a canopy created based on Origami techniques. Accessible digital simulation platforms were introduced and quantitative radiation analysis and qualitative radiation visualization were grinded in order to discover the most robust factors acting on the design of the canopy.

The paper presents a brief literature review on the origin, implementation and applications of Origami design in general and when it was specifically applied to a parametric design for radiation simulation.

The main purpose of this article was to create a complex parametric geometry based on Origami shapes and analyze some of the main factors with potential contribution to the incidence and transmission of Solar Radiation in the Canopy, using Factorial Analysis.

Among the main conclusions obtained, it is highlighted that, regarding the Factorial Analysis, the most robust factor observed in both analysis was a first order factor relative to the Canopy slope. The Canopy Orientation, although important to the conception of the model and somewhat representative, provided a smaller contribution. For the Cardinal Orientation Experiment, the Canopy Slope accounted for 71.55% of the total contribution, which was 87.15%. The second order factor accounted for 8.02%, relative to Slope and Orientation combined.

The analysis of the 5°, 15° and 20° slopes has proven that the differentiation of the inclination impacts the design, the amount of radiation received by the surface and the user comfort level.

The adaptive Comfort Model for 5° indicated a 67.7% total comfort hours with 16.7% PH and 15.5% PC. For the maximum slope of 20°, representative of a typical slope adopted in Brazil, the simulation shows a percentage of 74.0% of comfortable hours with 15.4% PH and 10.6% PC for a natural conditioned space.

A considerable part of the percentage of time in discomfort is related to hours before 8 AM mainly during winter and fall.

The results demonstrate that, together with the computational design technologies and the simulations available for the performance analysis of shading elements with complex shapes, the understanding of the solar geometry is essential for a selective admission of solar radiation.

Although the simulation was run for Viçosa MG (Latitude 20° 45 ′14 ″S, Longitude 42° 52′ 55″ W, Altitude 648 m), the parameterization allows it to be inserted anywhere else and the simulation requires only another weather file.

As an ongoing research, the next endeavor encompasses daylight evaluation and multi-objective optimization techniques to find trade-offs among different optimization objectives.

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4 CHAPTER 4 – SIMULATION-BASED OPTIMIZATION FOR AN ORIGAMI SHAPED CANOPY IN TRANSITIONAL SPACES

ABSTRACT

This study comprehends the developing process of a simulation-based optimization (SBO), using the Octopus® plugin for Grasshopper®. This study aimed to optimize an Origami-inspired canopy designed to allow solar radiation and daylight indoors. As optimization objectives, we employ the maximization of Physiological Equivalent Temperature (PET) and Useful Daylight Illuminance (UDI). The method starts with shape optimization, considering the exclusion of non-robust parameters, dismissed through factorial analyses performed in earlier works. The second step regards computational simulations for the admission of solar radiation and daylight performance into transitional spaces, followed by a comparative evaluation of the best solutions generated through the simulation process. We ran the simulations using Ladybug® and Honeybee® plugins, along with Radiance® and EnergyPlusTM. We simulated the canopy in three different transitional zones, which resulted in distinct shapes and performances. Transitional spaces were used because these locations are neither indoor nor outdoor, and comfort standards are rarely evaluated. As the main results, the optimization for three different zones generated maximum levels of comfort of 93.75% for PET Percentage Comfort and 93.8% for UDI for naturally conditioned spaces. These results denote that users are in thermal comfort in 93.75% of the evaluated time. In 93.8% of the simulated time, illuminance levels are between 100 and 2000lx, and therefore in agreement with the recommended levels.

Keywords: Multi-Objective Optimization; LadyBug; Honeybee; Octopus; Radiance; EnergyPlus; Transitional Zones; Physiological Equivalent Temperature; Useful Daylight Illuminance.

4.1 Introduction

The experience of space in architecture is dynamic, with intermittent interaction between spaces within a building or between indoors and outdoors. (POTVIN, 2000)

Research on thermal comfort often concentrates on internal environments (CHUN; KWOK; TAMURA, 2004). Notwithstanding, in the last two decades, there has been substantial research on outdoor thermal comfort (CHEN; NG, 2012; PENG; FENG; TIMMERMANS, 2019; SHOOSHTARIAN; RIDLEY, 2017). In architecture, areas that occupy both, inside and outside, deserve investigation due to their aesthetics and potential to save energy. (CHUN; KWOK; TAMURA, 2004)

Building simulations have been steadily established as a part of computational applications for the design process over the last two decades. The primary objective of their use is to run a performance analysis that informs, for instance, more efficient design alternatives that satisfy multiple criteria (YIGIT; OZORHON, 2018). They help speed up the design process and increase building efficiency due to their broader range of design variants, which leads to more optimal designs. (NGUYEN; REITER; RIGO, 2014)

Along with the simulation tools, the Simulation-Based Optimization (SBO) has been increasingly employed to manage complex engineering systems, achieving optimal solutions (or a solution near to the optimal) with less time and labor. (NGUYEN; REITER; RIGO, 2014)

SBO investigations mostly regard the selection of construction types and materials as optimization parameters. Fewer studies consider basic shape variables such as window-to-wall ratio and orientation. (FANG, 2017)

Concerning optimization objectives, researches are mainly focused on energy performance, thermal comfort, and environmental impacts. (FANG, 2017)

Acknowledging that the building envelope determines daylight admittance and thermal exchange with the outdoors, the importance of the built environment in the total energy consumption should be highlighted. In this scenario, solar shading devices can improve energy performance and thermal comfort. (CARTANA, 2018; CHO; YOO; KIM, 2014; FAJKUS, 2013)

Besides, we observe the impact of the advancement of digital tools and the changes in design processes. According to Oxman (2006), increased production processes have been observed in contemporary architecture. Furthermore, the appropriation and adaptation of digital manufacturing processes have resulted in technological innovations, which allow greater design freedom and customization of building components. (CARTANA, 2018; KOLAREVIC, 2005)

This paper strives to probe and perform an SBO for an Origami-inspired canopy in transitional spaces. As optimization objectives, we employ the maximization of Percentage Comfort for Physiological Equivalent Temperature (PET) and average Useful Daylight Illuminance (UDI).

This paper is part of ongoing research and intends to investigate the performance-based design process for a modular canopy through parametric modeling, computational simulations and optimization procedures. The parameterization of the Origami-shaped canopy and the selection of optimization parameters and objectives were elaborated in previous work (LUCARELLI; CARLO, 2019), using the Rhino3D+Grasshopper® suite.

4.2 Literature Review

4.2.1 Energy Consumption and Building Performance

Increase energy consumption resulted in a shortage of energy resources and environmental deterioration (ZHOU et al., 2019). The building sector is one of the largest energy consumers in the world (YANG; LAM; TSANG, 2008). It uses 45% of the total primary energy requirement and 30% of carbon emissions worldwide. (LOPES; CÓSTOLA; LABAKI, 2017; PÉREZ-LOMBARD; ORTIZ; POUT, 2008; YANG; LAM; TSANG, 2008)

In the United States, roughly 50% of its energy is consumed in the construction and operation of buildings. Building and construction sectors account for 81% of the total electricity expenditures. (BADER; ZITZLER, 2011)

In Europe, buildings consume more than 40% of the primary energy and are among the largest end-use consumer sectors. Non-residential buildings expend 25% of the European building stock. Almost 50% of the final energy consumption in Europe is used for heating and cooling, and 80% of this consumption is attributed to office buildings. (D’AGOSTINO; CUNIBERTI; BERTOLDI, 2017; KIRIMTAT et al., 2019)

In Brazil, the building sector spends around 50.7% of the national total energy demand. Commercial buildings account for 34% of this amount. (PEREIRA et al., 2017)

According to Yu and Su (2015), seven factors affect energy use in buildings; the outdoor climate, the physical characteristics of the building, building services, behavior of the occupants, indoor environmental quality, social and economic factors and user-based features.

It is important to address the physical characteristics of the building to reduce energy expenditure and improve its performance. This factor also promotes a better understanding of how buildings perform since they comprise non-spatial variables that affect the final design. (KO, 2013)

Energy performance depends on decisions made in different design stages, essentially the early ones. The building design is a complex process in which specialists from different fields contribute to the decision-making to meet all performance criteria (YIGIT; OZORHON, 2018).

The use of shading devices, for instance, usually helps reducing solar heat gains but also leads to a reduction of natural daylight and hence, an increase in artificial lighting and energy consumption (CARUSO; FANTOZZI; LECCESE, 2013). Therefore, finding effective alternatives that meet multiple standards is challenging. A thorough process with adequate material selection is required to decrease the initial and long-term operational costs of the building. (YIGIT; OZORHON, 2018)

For instance, Cheun, Fuller and Luther (2005) observed an energy-saving potential of 31.4% when adjusting the insulation of building envelopes. In a different investigation conducted by Chan et al. (2009), a double-skin façade in Hong Kong saved 35% of total cooling demand. For a high-rise building in Greece, simulation results revealed that thermal insulation in walls, roof, and floor decreased cooling demand by up to 40% (SPYROPOULOS; BALARAS, 2011).

Thermal performance researchers, Bader and Zitzler (2011) reduced direct beam radiation up to 75%. They considered the use of solar control mechanisms in buildings while maintaining natural ventilation and good visual access to outdoors. For a similar study, Yao (2014) developed computational simulations for studying adaptive shading devices that prevented undesirable solar heat gain, which allow daylight indoors.

Kirimtat et al. (2019) developed an MCDO for an amorphous shading device, aiming to maximize illuminance levels, using dynamic measures while minimizing Total Energy Consumption (TEC). As a result, he managed to keep average UDI between 52.03% and 57.13%, while reducing TEC.

Cartana (2018) has also incorporated radiation and daylight simulation-based optimizations to the process of designing a parametric shading. He minimized the direct beam radiation and applied a series of dynamic measures, such as Useful Daylight Illuminance (UDI). Grobman, Capeluto, and Austern (2017) also investigated louvers to ensure proper illuminance and radiance levels indoors and reached 33.68% better UDI than unshaded window solutions.

4.2.2 Building Performance Simulation

In recent decades, applications of computer simulation for handling complex engineering systems have emerged as a promising method. (GARBER, 2009)

Even though Brazil has sustainable construction manuals and guidelines from certification bodies, such material addresses slender buildings with lengthy façades towards north and south and windowless façades for the other orientations. These practical rules cannot be applied to different building geometries (CAMPOS; CELANI, 2017). Thus, it is essential to use computational simulations when working with the performance-based design process. (GOKMEN, 2013)

Besides computational simulations, building energy modeling and simulation can predict a building energy performance before its construction (NGUYEN; REITER; RIGO, 2014). It enables us to analyze the energy consumption of the constructed building at the design stage to speed up the design process, increase efficiency, allow the exploration of multiple design variants and lead to more optimal designs.

Wong (2017) presented an extensive review of computer simulation tools for daylighting. The most frequently used programs are Radiance®, Ecotect®, DOE®, Daysim®, and EnergyPlusTM. The two most commonly used calculation methods in daylight simulation programs are ray-tracing, which is a view-dependent algorithm utilized by Radiance®, and radiosity, which is a scene-dependent algorithm used in Relux®. (YU; SU, 2015)

According to Yu and Su (2015), Radiance® is the most current daylight simulation tool that uses backward ray-tracing. It is extensively applied in daylight-related investigations and validated by researchers such as Ochoa, Aries, and Hensen (2012). Nonetheless, it has a significant drawback, which is the absence of a user interface. The software system is usually incorporated as a simulation engine within other tools, such as Daysim®, Diva®, and Honeybee® for Grasshopper®. (OCHOA; ARIES; HENSEN, 2012)

EnergyPlusTM is one of the most accessible software system for building simulation analysis. It is an advanced whole-building energy simulation engine that can be used to model consumption in buildings. EnergyPlusTM simulation results are highly accurate, based on ASHRAE Standards, and validated by different researchers. (ANDJELKOVIC; MUJAN; DAKIC, 2016; MATEUS; PINTO; DA GRAÇA, 2014)

Ladybug® and Honeybee® are energy and daylight modelling plug-ins for Grasshopper®. Ladybug® imports standard EnergyPlus Weather files (.epw) into Grasshopper®, providing a variety of interactive graphics to support the decision-making process during all stages of design. It also automates and expedites the calculations, providing easy to understand, analyze, and manipulate graphical visualizations using Rhino® modelling interface. It also allows users to work with validated energy and daylight engines, such as EnergyPlusTM, Radiance® and Daysim®, exempting the need for further validation. (ROUDSARI; PAK, 2013)

Honeybee® is an extension of Ladybug® that enables the user to work directly with Radiance®, Daysim®, and EnergyPlusTM. It runs analysis for advanced building masses. It also automates the process of intersecting the masses and finding surfaces, so the user needs only to provide floor heights and the internal activities for each zone. Honeybee® provides several visualization components, allowing users to further examine the results.

The modeling process begins in Grasshopper® with parametric design variables and building geometry. Ladybug® and Honeybee® provide the modules for daylight and energy simulation.

In the daylight modeling process, the building zones are connected to the Radiance material component to insert a reflectance. Then, the materials are connected to the daylight simulation component, as well as the weather file and daylight sensor placement. The Radiance® daylight simulation component generates an output that feedbacks Ladybug®. After the simulation, Ladybug® imports the result files back to Grasshopper® and renders the annual lighting schedule. (FANG, 2017; ROUDSARI; PAK, 2013)

Regardless of the desired geometry, computational simulations can be applied in three stages of the design process. They have a stronger generative contribution if employed during the conception stage. If applied to the design process, they allow testing ideas and solutions. If they are adopted in the final stages, they enable performance evaluations. (UMAKOSHI, 2014)

According to Gokmen (2013), the later they are utilized, the more limited they are by predetermined component configurations. They allow assessing building performance but are restricted without the possibility to change all parameters. (GOKMEN, 2013; OXMAN, 2006)

The incorporation of computational simulations as a design factor in the initial stages is a very meticulous procedure. Østergård, Jensen and Maagaard (2016) consider that they should be implemented as soon as possible so as to achieve better results. However, their applicability is still limited in early design stages due to time-consuming modeling, rapid design change, and input uncertainties. Still, predicting the consequences of initial decisions is essential, since unfavorable settlements will make it more strenuous and expensive to meet high-performance goals. (ØSTERGÅRD; JENSEN; MAAGAARD, 2016)

4.2.2.1 Parametric Simulation and Parametric Modeling

Along with comfort and energy efficiency matters, we can observe that the use of digital tools is redefining architecture (CARTANA, 2018; PETERS, 2013). Architects are exploiting these tools and creating new possibilities in design, fabrication and construction.

Researchers have seen multiple advances in the numerical analysis of the performance of daylit spaces in the first decade of the 21st century (WIENOLD; CHRISTOFFERSEN, 2006). These progressions include climate-based daylight simulations, more refined glare prediction, and new evaluation methods for light redirecting devices. They are important to support decision-making and facilitate the conception of complex surfaces[1]. (DUNN, 2012; MIYASAKA, 2017; OXMAN, 2006; PETERS, 2013)

In building science, designers use dynamic simulations to analyze thermal and energy efficacy and achieve specific objectives. The most traditional approach to dynamic simulation is the parametric simulation. Initially, it consisted of changing one

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[1] Complex surfaces are fluid, created by spherical solids or curved volumes. They have complex morphology and materials and maintain close relationships with information technologies. These surfaces combine a great number of competencies striving to organize the constructive process (PAOLETTI, 2006).

simulation input variable and keeping all others constant, which allowed estimating the effect of each variable on building performance.

However, this method was analogical and non-interactive. It omitted the identification of optimal design solutions since it did not acknowledge the intercommunication between variables.

In contrast, parametric modelling is a design tool for the creative process. The variability of solutions presented by this tool helps evaluating several alternatives before choosing a definitive solution. Therefore, computational simulation can be integrated as an essential decision-aiding tool. (KOLAREVIC; MALKAWI, 2006)

The term parametric originates from mathematics and refers to using specific variables to manipulate the equation results (FRAZER, 2016). Parametric modelling, different from parametric simulation, refers to the automated parameter-based generation of any design element, which means managing the generation and alteration of any component with specific algorithm-generated rule-sets. (ELTAWEEL; SU, 2017)

Parametric modelling started to be used in 2008, with the implementation of the first parametric design software. The most popular software is Grasshopper®, which provides different plugins in many disciplines such as architecture, urban planning, structural study, environmental analysis, and many others. (ELTAWEEL; SU, 2017)

In Brazil, publications on the use of parametric modelling software have emerged over a decade in national conferences and scientific events (ANDRADE; RUSCHEL, 2009). Parametric simulation has been employed in energy efficiency studies for almost two decades in Brazil, but only recent evaluations have acknowledged geometric parameters and parametric modelling, due to the computational advances in the 2010s. (SANTANA; GUIMARÃES; CARLO, 2015)

The solar shadings of complex geometry are an example of a shape parameter that would be impractical without the aid of processing tools. (SANTANA; GUIMARÃES; CARLO, 2015)

Even though relatively new in Brazil, the implementation of shape parameters in building’s form optimization has been investigated in many publications, especially with a numerical approach by using multi-objective optimization and genetic algorithms. (CARTANA, 2018; CARUSO; FANTOZZI; LECCESE, 2013; CHO; YOO; KIM, 2014; FANG, 2017)

In architecture, digital shape modelling has been using the term parameterization. Its re-signification consists of automation of the design process, in which rules are defined by parameters to create, analyze and modify shapes to meet different criteria. These parameters can vary from geometric determinations to solar gain and structural rigidity, allowing design optimization and more intelligent structures (CAMPOS; CELANI, 2017). This computerization also allows reducing the time spent in the design process and providing more precise results.

By itself, parameterization can provide complex solutions. However, for some issues, including structure, lighting and thermal performance, it is necessary to use computational simulations. Combining parameterization and optimization allows generating solutions that correspond to better building performance. It also produces a method that goes beyond the dynamic generative potential of the parameterization. (CAMPOS; CELANI, 2017; KOLAREVIC; MALKAWI, 2006)

4.2.2.2 Simulation-Based Optimization

Designers can achieve building thermal performance through two approaches: trial and error or optimization algorithms[2] (GOSSARD; LARTIGUE; THELLIER, 2013). Although the trial-and-error method can generate satisfactory solutions, optimization is likely to provide the best solutions, based on selected objectives (MAGNIER; HAGHIGHAT, 2010). For this reason, simulation-based optimization (SBO) can be a process to achieve better-performing building designs. (DELGARM et al., 2016)

SBO has been applied since the 1980s on an international scale. However, due to the implementation of shape modelling as parameterization, since the 2010s, considerable research on SBO for building energy consumption has been developed. These researches aim to understand the most relevant building parameters and architectural configurations to promote energy efficiency. (DELGARM et al., 2016)

SBO is a design procedure that helps designers finding the best resolutions for a particular goal. Optimization is related to the process of seeking solutions closer to an optimal point, which more effectively meets an intent. (NGUYEN; REITER; RIGO, 2014)

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[2] Optimization algorithms are classified into two main categories: the conventional gradient-based method and the direct, gradient-free search. Gradient-free direct search methods are best suited for application in buildings. They handle discontinuous and multiobjective variables and can find an acceptable solution (almost optimal solution) using less computing time compared to other algorithms. (MAGNIER; HAGHIGHAT, 2010)

Optimizing means to minimize or maximize a function by systematically choosing values or real variables within a viable set. However, building optimization remains a complex science. It involves a large number of variables, non-linear equations, and long simulation time (LARTIGUE; LASTERNAS; LOFTNESS, 2014). Moreover, optimization allows exploring a large number of design solutions efficiently, but transferring a building design problem into the mathematical domain is a difficult task. The development of parametric modelling and design, building performance simulation and optimization technologies has made it possible to optimize building performance.

The optimization process usually requires two types of inputs: variables and objective functions. In building performance optimization, variables are the values that control the geometry or any property related to design. Fitness functions are the building performance metrics calculated by any simulation tools. (MACHAIRAS; TSANGRASSOULIS; AXARLI, 2014)

An optimization problem can be mono or multi-objective, depending on the number of objective functions. Nguyen, Reiter, and Rigo (NGUYEN; REITER; RIGO, 2014) identified that the first alternative is the most common, corresponding to 60% of the published scientific researches. However, multi-objective optimization problems (MOPs), or Pareto optimization, is more likely to approach real problems. MOPs deal with conflicting design criteria using two or more objectives to address essential limitations found in mono-objective optimization problems. (DELGARM et al., 2016; NGUYEN; REITER; RIGO, 2014)

Engineering designs often require conflict resolution. There are two conventional means of achieving this goal. The first one is by using a weighted-sum approach, in which the various objectives are merged into a single objective, and then optimized. The second alternative is by using MOPs, which explore the trade-off between each objective. (EVINS, 2013)

Based on optimization output data analysis, the designer can choose between the solutions within a curve of optimal solutions (NGUYEN; REITER; RIGO, 2014). Most studies on the field of MOPs usually strive to find a set of solutions that approximates to the Pareto-optimal set. (BADER; ZITZLER, 2011; NGUYEN; REITER; RIGO, 2014)

4.2.2.3 Genetic Algorithms

Genetic algorithms are among the most commonly applied in optimization (EVINS, 2013). They were inspired by Darwin's theory of evolution, in which populations of solutions are created and evaluated according to their performance towards the proposed objectives. Concepts of diversity are common, including crossover, exclusion and genetic mutation (random changes).

According to Bader and Zitzler (2011), multi-objective genetic algorithms (MOEAs) implement a combination of Pareto dominance and a diversity measure (ZITZLER; THIELE; LAUMANNS, 2003). Those methods appear mostly in bi-objective scenarios, but difficulties emerge when the number of objectives increases.

HypE is a Monte Carlo hypervolume algorithm created to overcome the challenges generated by MOPs. It is the only quality indicator algorithm known to be adequately sensitive to Pareto dominance, which is desirable for MOPs. (BADER; ZITZLER, 2011)

According to Yu and Su (2015), to achieve a better building performance, we must consider three factors: the building design, the systems, and the occupants, who account for a significant part of an efficient building. Designing works as an interactive process, requiring the rethinking of some fundamental aspects. Therefore, optimizing the design process reduces the need for redesign.

Octopus® is an attractive plugin for working with MOPs inside Grasshopper®. It allows the user to work with bi or multi-objective optimization and has a diversify parameters option built-in, which increases the search field for solutions.

The diversify parameters toggle adds an internally handled goal, which seeks to maximize each solution distance to all other solutions in the genetic space. It works with any genetic algorithm, considering that they only differ in truncation and selection of solutions.

The insertion of the diversify parameters toggle leads to a slight difference in the convergence, due to the maintenance of its diversity behaviour.

Octopus® also allows using two MOEAs: HypE and SPEA2. Apart from determining the population size for each generation, it enables the user to set a maximum number of generations before the optimization process. The engine also prevents the optimization from being interrupted when faced with impossible cases and skips to the next solution when it reaches a maximum running time. (FONSECA et al., 2016)

The user can rely on a convergence diagram that presents the parameters' range for the selection of the best results. Another alternative is the visual selection, by the analysis of the performance indicators plotted in the Pareto Chart.

4.2.3 Transitional Spaces

Researchers use a variety of terms when referring to environmental conditions within a space (CHUN; KWOK; TAMURA, 2004). Some use the expression transitional as a synonym for the term transient. It can mislead the reader because transitional can mean architectural space, the response of the occupant, physical conditions, or a combination of all these factors. (CHUN; KWOK; TAMURA, 2004)

Transitional zones are the in-between architectural spaces, where the indoor and the outdoor climate meet and are modified without mechanical control. In these spaces, the occupants experience the dynamic effects of the weather change.

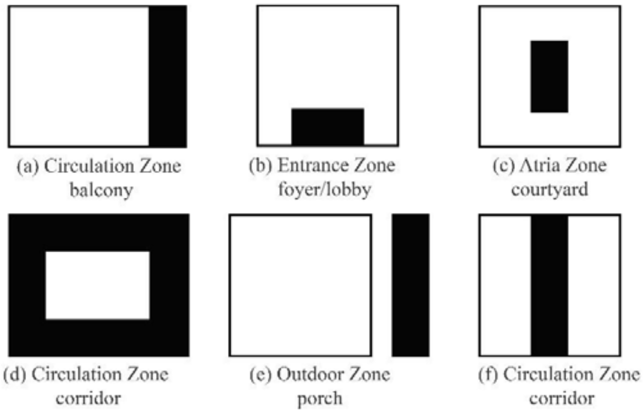
Transitional spaces can also be used to alter the expectations of occupants for environmental conditions when moving around a building.

Transient conditions in indoor and transitional spaces are dynamic, variable, unstable, or fluctuating (CHUN; KWOK; TAMURA, 2004). They are associated with many variables, such as solar radiation, temperature and wind. They may also occur within an interior space, where direct beam radiation and temperature swings may not be desirable. In transitional spaces, the transient conditions are a consequence of the outdoors. (CHUN; KWOK; TAMURA, 2004; POTVIN, 2000)

For some transitional spaces, the occupation is short-termed and, therefore, disregarded by designers. However, the opposite is more likely to be accurate, due to the non-conditioned and opened space impact on the building energy use, which affects user perceptions and expectations. (PITTS, 2013)

Transitional spaces deserve study and treatment from another perspective other than comfort standards when striving to set design parameters and ranges of assessment indices. (GARBER, 2009)

Figure 1 - Types of Transitional Spaces.



Source: Chun, Kwok and Tamura (2004), Pitts (2013), edited by the Author.

Transitional zones can be halls, canopies, lift lobbies, corridors and staircases. According to Chun, Kwok, and Tamura (2004), and Pitts (2013), they are distributed into six broad types:

(a) Sheltered space, connected to the building (or between buildings), in which outdoor conditions predominate. They can be a balcony, a porch, a corridor or a covered street;

(b) Entrance areas with strong connections to the exterior, such as a hotel lobby or an atrium with continuously mixed conditions. Generally, entrance zones are crucial in modifying thermal expectations and experiences for users. Though residence time may be short, such spaces reduce the thermal shock, providing time for adaptation;

(c) Area set into the middle portion of an extended façade of a rectangular building. An atria zone or a courtyard;

(d) External perimeter corridor around the outside of the building;

(e) Semi-occupied space in which occupants gather for an extended time, which is not attached to a building and is virtually an outdoor room. It is entirely influenced by the outdoor climate. Pergolas, bus stations or pavilions;

(f) Space parallel to the long axis of the building, such as a circulation zone or a corridor.

4.2.3 Assessment Indices for Transitional Spaces

Useful Daylight Illuminance (UDI) preserves much of the interpretive simplicity of the common daylight factor (DF) approach (NABIL; MARDALJEVIC, 2006). UDI is employed in different ways, depending on the evaluation scenario. It helps interpreting climate-based analyses of illuminance found on weather files. UDI employs realistic, time-varying sky and sun conditions, predicting levels of absolute daylight illuminance per hour in each point of the space. In contrast, the conventional DF provides a single number for each point in space.

UDI is a dynamic measurement, mainly used for evaluation of admission and distribution of daylight. It establishes a lower limit of 100 lx and a higher limit of 2,000 lx for the Daylight Admission (DA). (REINHART; MARDALJEVIC; ROGERS, 2006)

UDI and DA are expressed as a percentage of time per year in which daylight levels are within the desired range for the occupied hours.

Physiological Equivalent Temperature (PET) is another index for transitional spaces. It is based on the Munich Energy-balance Model for Individuals (MEMI), which regards the energy balance of individuals. PET is an index for calculating thermal comfort adapted to outdoor conditions, using the equation of human thermal equilibrium in a state of uniformity. (MATZARAKIS; MAYER, 1996)

Its values are estimated in degrees Celsius. It is defined as the temperature, in a given environment (indoor or outdoor), equivalent to the air temperature of an internal reference environment. (HÖPPE, 1999)

PET is equivalent to the air temperature required to reproduce the core and skin temperatures for a standardized person in a standardized space. This person has a working metabolism of 80 W of light activity and 0.9 clo of heat resistance. (GUIMARÃES, 2016)

One of the advantages of PET is that the climate variables are the same as those used in other comfort indexes, which enables comparative analyses. Similar to Fanger’s Predicted Mean Vote (PMV), PET uses the climatic variables: air temperature, relative humidity, air velocity, and mean radiant temperature to estimate the thermal sensation.

4.3 Research Methodology

This work is an exploratory approach, with experimental development (GROAT; WANG, 2013), inserted in the topic of Building Performance Simulation (BPS), with simulation-based optimizations for daylight, thermal performance, and comfort.

We organized the method according to the following steps, based on the research of Cartana (2018), and Fang (2017):

(1) Shape optimization considering the exclusion of non-robust parameters dismissed through factorial analysis in previous work (LUCARELLI; CARLO, 2019)

(2) computational simulations of the admission of solar radiation and daylight performance in transitional spaces;

(3) comparative evaluation of the best solutions generated in the simulation process.

4.3.1 Optimization

Using Rhino3D+Grasshopper® parametric suite, we developed a script for an Origami shaped Canopy as a shading device element. The geometry selection relies on the exploration of the potential of the modelling tool, besides investigating the behaviour of complex shapes for solar shading devices.

For the sake of optimization, we adopted Octopus® for Grasshopper® because it enables the user to work with MOPs and the diversify parameters option, which increases the chances of algorithm exploration in the entire search field of solutions. In this study, we used HypE because of its capacity to deal with multiple criteria.

The optimization objectives are the maximization of average UDI and minimization of thermal discomfort expressed by PET. Average Useful Daylight Illuminance (aUDI) is the sum of each UDI divided by the number of analysis points. Therefore, the maximization of the whole simulation grid should maximize each evaluation point.

We conducted the study for the city of Viçosa, MG, Brazil (Latitude 20º 45' 14" S, Longitude 42º 52' 55" W, Altitude 648 m) with a TMY3 Weather File (GUIMARÃES, 2016). Since the canopy was created using a parametric modelling script, the simulation-based optimization can occur anywhere, depending only on the weather file.

This research focuses on the canopy performance design process because of its higher sensitivity to solar radiation admission and heat gain in lower latitudes. Besides, canopies are more susceptible to the visual discomfort caused by excessive intake of daylighting if treated as semi-permeable structures.

Table 1 - Assessment Indices PET (Physiologic Equivalent Temperature) according to Mayer and Matzarakis

PMV	PET	Thermal Sensitivity
-3.5	4 °c	Very Cold
-2.5	8 °c	Cold
-1.5	14 °c	Cool
-0.5	18 °c	Slightly Cool
0.5	23 °c	Comfortable (Neutral)
1.5	29 °c	Slightly Warm
2.5	35 °c	Warm
3.5	41 °c	Hot
		Very Hot

Source: Adapted from Matzarakis and Mayer (1996)

We started Octopus® with a population size of 30 and Max generations of 30, based on previous investigations that combined simulation software, the required output, and the number of parameters (LUCARELLI; CARLO, 2019). During the simulation, we adopted the convergence of solutions as a stopping criterion. We define the convergence point by watching the parameter convergence chart provided by Octopus®.

For PET, we cannot maximize or minimize the values as they range from -3.5 to 3.5 (Table 1). Therefore, we chose to maximize Percentage Time Comfortable (PTC), one of the outputs of Honeybee® Thermal Comfort Indices, which approximates PET to 0.0 (comfortable or neutral). The table also presents the correspondence of PET bands by variations of the PMV, on the seven point scale.

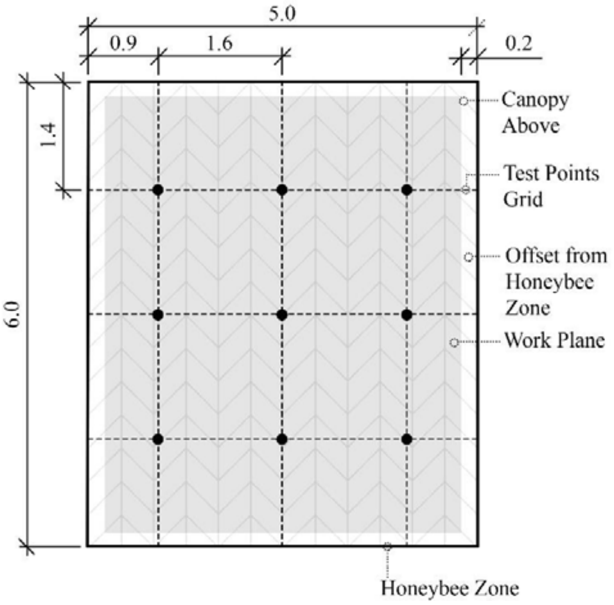
4.3.1.1 Optimization Objectives

In Honeybee®, the analysis grid for UDI is the same as the daylight sensors for annual simulation. The grid height was placed just below the canopy. The distance between nodes was 1.5 m, generating 9 points (Figure 2). To avoid interference from daylight that would not go through the canopy, we created an offset of 0.2 m.

For the PET analysis, the software interprets the whole space and generates one value of thermal sensitivity. The assessment plan position in Grasshopper® was the same as the UDI analysis grid, considering an identical offset from the Honeybee® Zone.

Concerning the climate aspect, Viçosa is in the Zona da Mata of Minas Gerais and has two provisions, according to the classification of Köppen-Geiger. The first one is Tropical Wet and Dry Climate (Aw) in the lower parts of the territory. The second, Subtropical Highland Variety of the Oceanic Climate (Cwb), in the highest portions. For this reason, we adopted the PET input for Tropical and Subtropical Humid Climates.

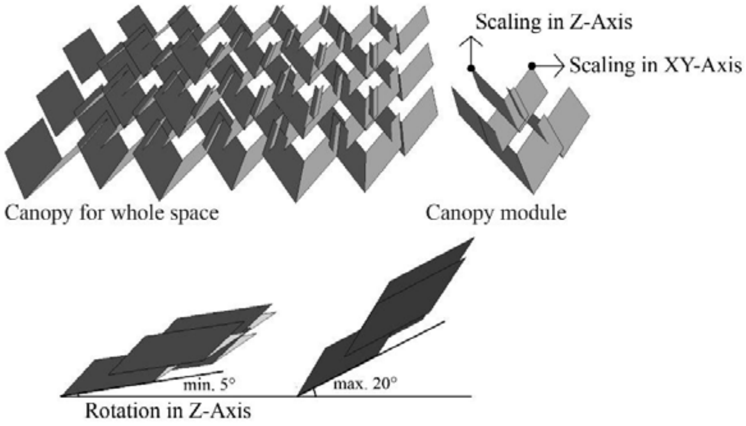
Figure 2 - Useful Daylight Illuminance plane of analysis.



Source: The Authors.

4.3.1.2 Optimization Parameters

Figure 3 - Optimization Parameters applied on Canopy.



Source: The Authors.

The optimization parameters derive from previous work (LUCARELLI; CARLO, 2019) and consist of aperture variation and inclination. For the opening, we employed two parameters, scaling in Z-axis and XY-axis. The slope is generated by rotating points in the Z-Axis (Figure 3).

All openings face north to allow daylight all day, leading to possible maximization cases for UDI and PET.

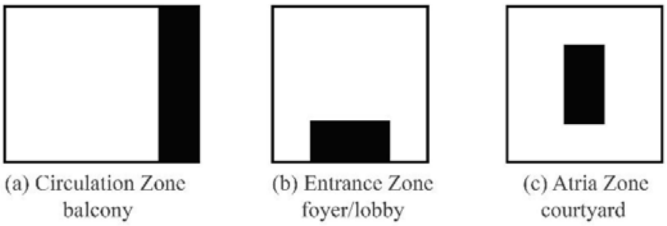
4.3.2 Simulation

Using the Honeybee® plug-in, we performed computational simulations of the admission of solar radiation and natural light. In all simulations, we positioned the solar shading device on a tiltable roof area.

4.3.2.1 Zones

Chun, Kwok, and Tamura (2004), and Pitts (2013) discuss six different transitional spaces, but highlight only three of them. In this research, we settled to work with these three options: Entrance Zones (foyers or lobbies), Circulation Zones (balconies), and Atrium Zones.

Figure 4 - Transitional spaces chosen.



Source: The Authors.

Despite having different properties, the Atrium Zones are Entrance Zones in Chun, Kwok, and Tamura's (2004) research. In this paper, they are a distinct type of transitional space, since they are affected by the outdoors only through the roof (Figure 4).

We conducted three main simulations. The first, represented by (a), did not have front or side context, which is a geometry that could block sunlight on the test geometry. In this first situation, the canopy attaches to a wall. We simulated PET only, since UDI requires an indoor space, averting the results from the proposed situation.

Metabolic rate is likely to be of slower walking pace or standing, occasionally higher or lower (Table 2). Clothing insulation is closer to outdoor measures.

For the second condition, the canopy attaches to three walls. The simulation space is within a building, such as a hotel lobby, where conditions change as people move in and out. For this option, we simulated PET and UDI. We created a Honeybee® zone below the canopy for UDI simulation. We treat the openings as super clear glass and allow natural ventilation for both simulations.

The third condition operates similarly. The simulation space is also within a building with context geometries on four sides. For this option, we simulated PET and UDI.

For both, the metabolic rate is likely to be at walking pace level or above, depending on speed movement (Table 2). Clothing insulation varies. For the Entrance Zone, clothing insulation is closer to the external measures or higher. For the Atria Zone, we worked with indoor standards. The period of residence for the second condition is likely to be short. For Atria Zones, time may vary according to the activity.

As Honeybee® simulation parameters, the wall and floor reflectance rates were 50% and 20%, respectively. The material for the solar control element was a gray-diffuse metal, with reflectance of 50%. The occupancy time was from 6 am to 6 pm.

For daylight admission simulations, we used average Useful Daylight Illuminance (aUDI) between 100lx and 2000lx, which corresponds to the summation of UDI percentages divided by the number of analysis points.

We performed simulations for all sunshine hours during one year.

Table 2 - Simulation Parameters for each space

Space	Metabolic rate (met)	Clothing insulation (clo)	Time of residence (min)
(a)	1.2 – 1.7	0.5 – 2.0	5 – 15
(b)	1.7 – 2.0	0.5 – 2.0	5
(c)	1.7 – 2.0	0.5 – 1.0	5 – 20

Source: The Authors

4.4 Results and Discussions

4.4.1 First Condition – Circulation Zone

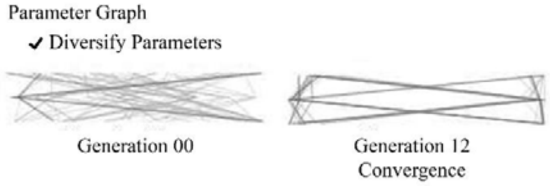
For the first condition, PET Percentage Comfort is the only optimization objective, which configures a mono-objective optimization. We activate the diversify parameters toggle to add another objective to the process, which creates a Multi-objective Problem (MOP).

Running the optimization with the diversify parameters changed the range of solutions and created slight differences in the convergence and diversity maintenance behaviour.

When running the SBO without the diversify parameters, the convergence occurred on the seventeenth generation. With the option selected, the convergence happened on the twelfth (Figure 5).

As observed, in Generation 00, all parameters are scattered throughout the graph. As the optimization advances, the lines move closer together. A smaller overlap indicates that the combination of parameters and variables are not as expressive as the variation of other parameters.

Figure 5 - Parameter Graph and Convergence in Octopus for the first condition.



Source: The Authors.

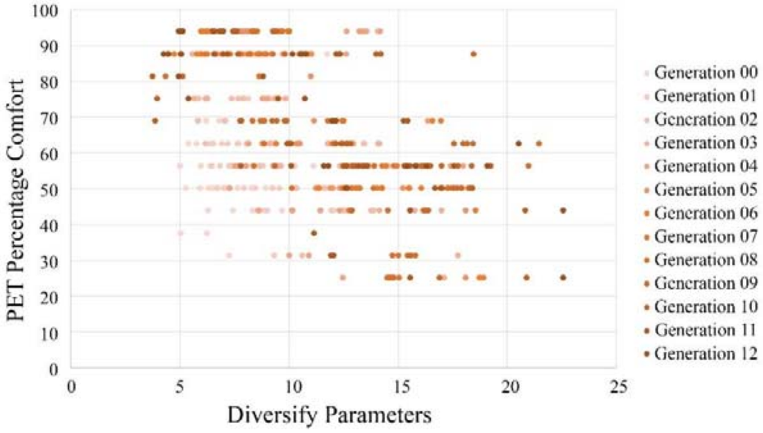
In Generation 12, the parameter scaling in XY-Axis, which performs the module opening, is the most expressive. It has the greatest effect on optimization. Opening in Z-axis is the least impactful.

Although both parameters apply to module opening, XY-Axis scaling was more expressive because it affects the number of hours a day the canopy admits daylight inside the transitional space. Z-Axis concerns a vertical opening, with less impact on the number of daylight hours.

Concerning optimization objectives, maximizing the PET Percentage Comfort caused PET to approach 0, which means a neutral thermal sensitivity.

For the first condition, the relation between PET and Diversify Parameters (Figure 6) shows the progression of the results towards 100% PET Percentage Comfort. The adoption of the diversify parameters' option enabled different geometries with the same PET levels, which means, more results with the same computational time. The wide variety of results indicates the importance of decision making in determining a final solution. There is a range of results that achieved the maximum PET Percentage Comfort of 93,75%, which indicates that other issues must be addressed to select the best of them.

Figure 6 - Solution for Diversify Parameters and PET objectives scattered in 12 generations.



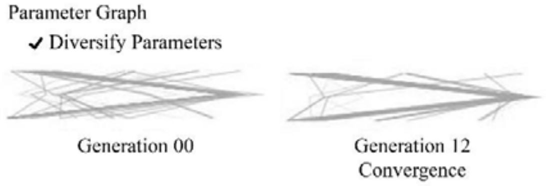
Source: The Authors.

The base case represents a simulation for the selected transitional space, with the context geometry and no canopy. This context geometry, as addressed before, is the building in which the canopy attaches. It could block sunlight in the transitional space but does not affect the canopy in this base case. In this circumstance, PET Percentage Comfort returned results of 0% with a PET of 3.5, indicating a very hot thermal sensitivity.

4.4.2 Second Condition – Entrance Zone

For the second condition, we used UDI and PET Percentage Comfort as optimization objectives. We also worked with the diversify parameters option to create a comparison between this condition and the first. Octopus maximized both, UDI and PET Percentage Comfort, and the convergence occurred on the twelfth generation (Figure 7).

Figure 7 - Parameter Graph and Convergence for the second condition.

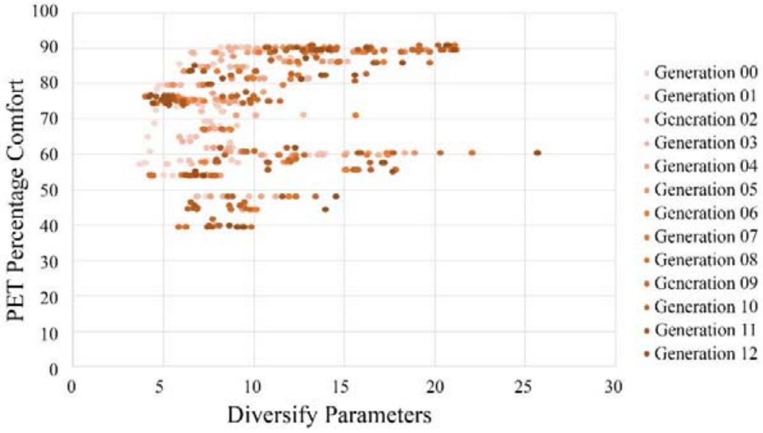


Source: The Authors.

Unlike the first condition, in the PET versus Diversify Parameters graph, the PET Percentage Comfort presents more scattered results (Figure 8) and, despite reaching a lower maximum, it has a higher minimum. Still, the diversify parameters provided a variety of results with the same PET level.

Concerning UDI and PET dispersion (Figure 9) the higher the illuminance, the lower the thermal sensitivity, tending to results higher than 0.0 for PET, since sunlight is composed of the visible light spectrum, infrared and ultraviolet energy. Infrared energy is an example of thermal radiation and, therefore, a mechanism of heat transfer.

Figure 8 - Solution for Diversify Parameters and PET objectives scattered in 12 generations.



Source: The Authors.

As the generations progress, UDI and PET Percentage Comfort advance on the Pareto Frontier. Higher values of UDI result in lower levels of PET due to admission of heat. An optimal selection should consider a balance between light admission and thermal sensitivity. For this reason, we select as an optimal design a point in the Pareto Front knee, which approaches the Utopia Point[3].

In general, the three last generations compose the Pareto frontier, which indicates conversion. In MOPs, all points on the Pareto front are potentially an optimal solution.

If we are to analyze the best solutions for the canopy, knowing that UDI and PET are conflicting objectives, we can choose extreme cases in which either UDI or PET are maximum.

The first extreme case would represent a maximum UDI of 93.8% with minimum PET Percentage Comfort of 53.8%.

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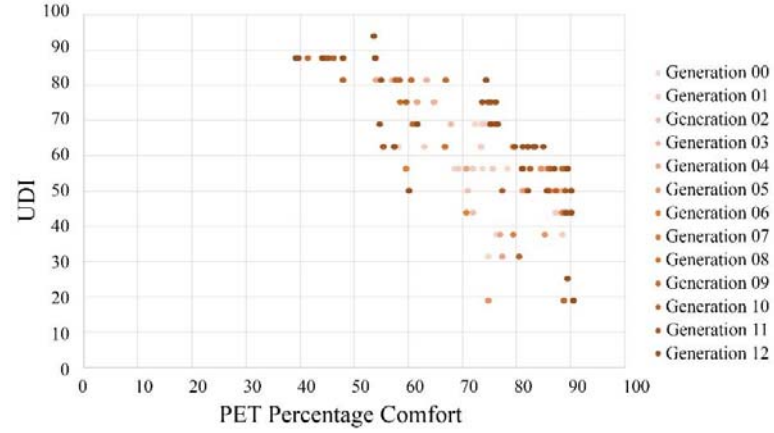
[3] A Utopia solution does not usually exist, but the Utopia point is an ideal standard in a Pareto optimal set. In the plot, the Utopia point has coordinates that simultaneously maximize both criteria, occupying the edge of the criterion space.

Figure 9 - Solution for UDI and PET objectives scattered in 12 generations.



Source: The Authors.

Thus, for 93.8% of the occupied hours in a year, daylight levels are within the range of 100-2000 lx and in 53.8% of the time, thermal sensitivity is within the comfort range.

The second extreme case consists of a PET of 90.7% and a UDI of 18.8%. In this case, daylight levels are within 100-2000 lx 18.8% of the simulated hours.

An intermediate case that would approach the Utopia point has a UDI of 62.5% and a PET of 85.1%. It is a balance between UDI and PET, with 62.5% of the occupied hours within daylight levels of 100-2000 lx and 85.1% of comfort hours.

Similar to the first simulation, the base case has a context geometry but no canopy. The context geometry for the Entrance Zone provides more shading and presents a maximum PET Percentage Comfort of 11.2%, with a UDI of 5%.

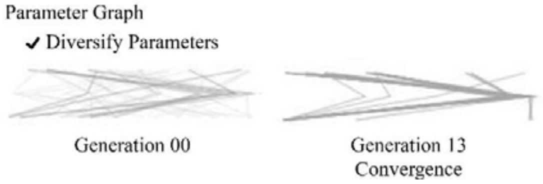
From 8760 simulated hours, the intermediate case accounts for 5475 hours with daylight levels between 100-2000 lx, while the base case has 438. For PET Percentage Comfort, the intermediate case offers 7455 hours in comfort, while the base case presents 981.

Once more, the selection of a final optimal configuration among the available points demands a decision-making process, which should consider qualitative parameters that are not used in MOPs.

4.4.3 Third Condition – A Zone

The third condition is similar to the second. We maximized UDI and PET Percentage Comfort using the diversify parameters' toggle, and the convergence appeared on the thirteenth generation (Figure 10).

Figure 10 - Parameter Graph and Convergence for the third condition.

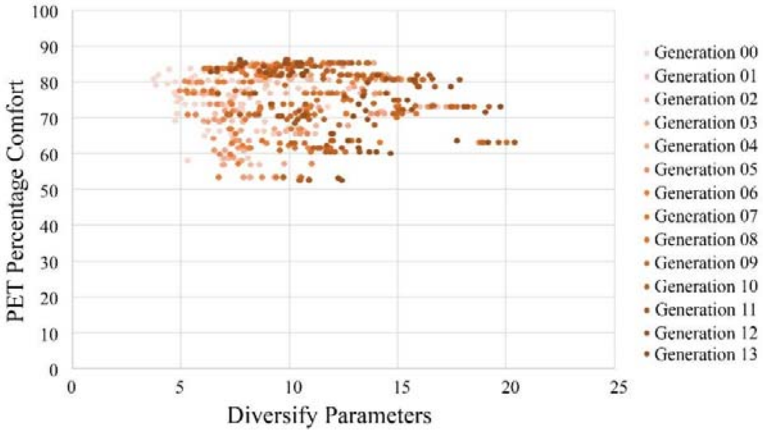


Source: The Authors.

When running the MOP without the diversify parameters' option, the convergence occurred on the seventeenth generation, which provided less optimal results with more computational time.

In this SBO, the analysis of the dispersion of Diversify Parameters and PET Percentage Comfort presented more concentrated results (Figure 11). The maximum PET Percentage Comfort is the lowest of all three conditions due to thermal sensitivity for cold. The minimum PET is the highest of all three simulations since the context geometry, even without canopy, prevents intense radiation and reaches higher PET values.

Figure 11 - Solution for Diversify Parameters and PET objectives scattered in 13 generations.

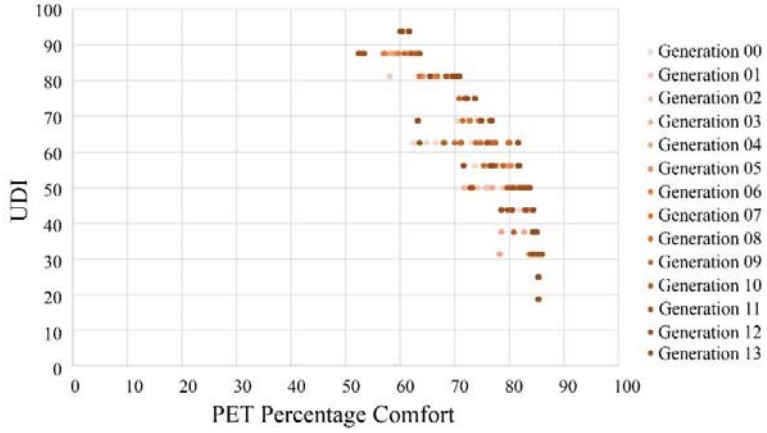


Source: The Authors.

The analysis of the PET and UDI dispersion (Figure 12) revealed that the context geometry also caused PET to reach higher values, compared to the other conditions, due to its higher minimums.

UDI values are slightly lower than those in the Entrance Zone, which is coherent, since the illuminance infiltrating the space derives from the canopy openings, and the context geometry blocks any other gains. In the Entrance Zone, the illuminance level also considers daylight coming from the front, where there is no context geometry. The last generations contain the best results and still form the Pareto front

Figure 12 - Solution for UDI and PET objectives scattered in 13 generations.



Source: The Authors.

If we follow the same selection criteria used for the Second condition, we can pick extreme cases and an intermediate result.

For the first extreme case, Pareto maximum UDI reached 93.8%, which indicates that, in 93.8% of the occupied hours, illuminance levels are within the range of 100-2000 lx. PET Percentage Comfort is 61.7%, which shows that 61.7% of the simulated time, thermal sensitivity is within the neutral range.

The other extreme situation returned a PET of 86.1% with a UDI of 18.8%. In this case, we achieve thermal comfort of 86.1% of the simulated hours. The illuminance levels are within the accepted range only in 18.8% of the cases.

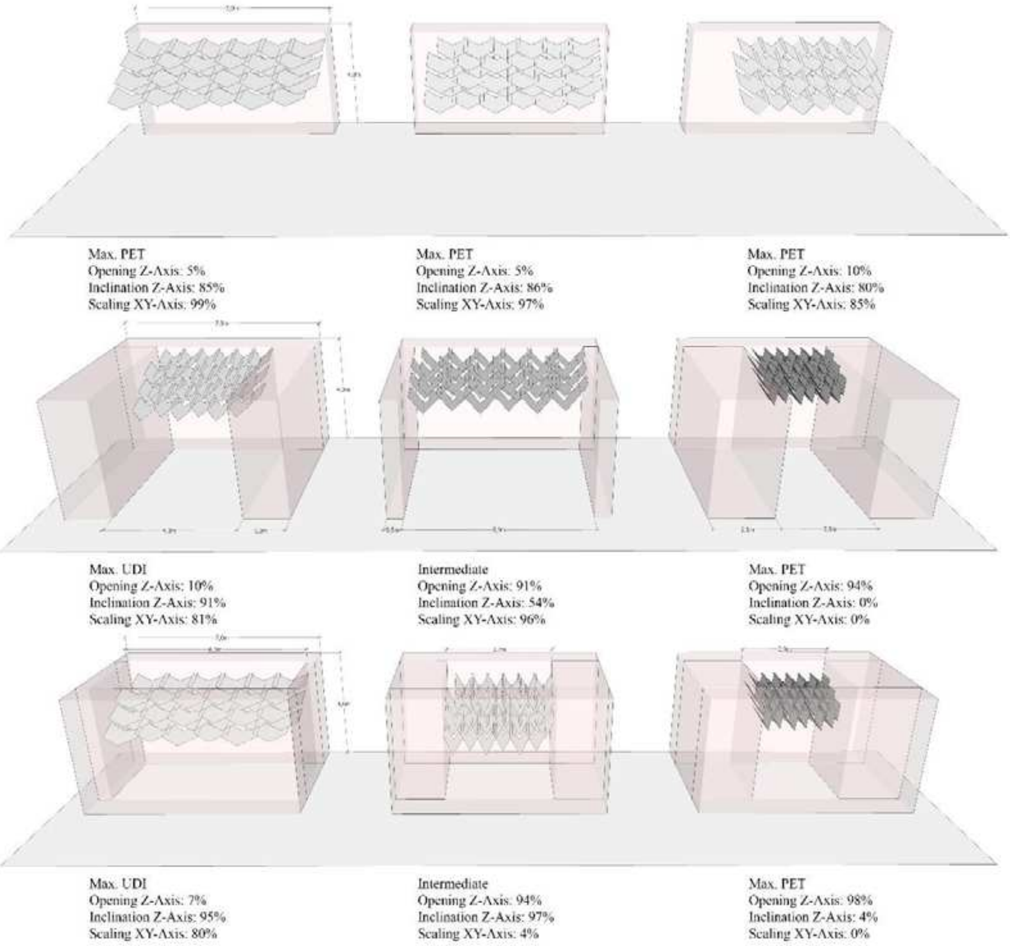
The intermediate solution, which is closer to the Utopia point, presents a UDI of 62.5% and PET of 82.7%. PET value is close to the second extreme situation, with a high percentage of time comfortable, if associated with ASHRAE 55's 80% adaptive comfort acceptance rate.

The base case has the context geometry, the surrounding Atria Zone, with no canopy test geometry. Even without the canopy, the context provides shading and presents a maximum PET Percentage Comfort of 14.2% and UDI of 13%. These results present the transitional spaces as passive strategies for shading and thermal comfort.

Out of the 8760 simulated hours, the intermediate case accounts for 5475 hours, with daylight levels between 100-2000 lx, while the base case has 1139. For PET Percentage Comfort, the intermediate case offers 7245 hours in comfort, while the base case presents 1244.

In Figure 13, we show all the selected cases with the optimization parameter percent. For the first SBO, we have one expressive parameter, which is the PET. The diversify parameters option changes accordingly, enabling other design possibilities. Changes in the design are subtle, but, as discussed in previous research (LUCARELLI; CARLO, 2019), we worked with robust optimization parameters that would greatly impact thermal sensitivity and daylight.

Figure 13 - Chosen options of Optimized results for Canopy Design.



Source: The Authors

These changes in the design may affect structure rigidity, material consumption, water runoff and other parameters not included in the SBO. These parameters can help with the of decision-making process. For example, when facing optimization results that returned the same PET and UDI values, water runoff and constructability could be decisive.

When examining the variations in the second and third conditions, the changes in design are more apparent. UDI meddles with the optimization process by raising XY-Axis values to collect more daylight and increase the illuminance values.

The more daylight injected inside the space, the higher the radiation values and thermal sensitivity. Consequently, PET and UDI are conflicting optimization objectives.

To achieve higher thermal comfort percent, PET Percentage Comfort manipulates Scaling in Z-Axis and XY-Axis, thus increasing the values for the first and diminishing for the second. We can see that, in the second and third conditions, the MOPs for UDI and PET showed XY-Axis values of 0% while trying to maximize the opening in Z-Axis.

4.5 Conclusions

This document is an exploratory project on the potential application of SBO tools to an Origami-inspired canopy. We continued to investigate parameters, such as module size and opening, to satisfy the optimization Indices for Transitional Spaces.

In a previous work, we applied parameterization, simulation and factorial analysis to determine the most robust optimization parameters that would contribute to the incidence and transmission of solar radiation in the canopy. We introduced digital simulation platforms, quantitative radiation analysis and qualitative radiation visualization, striving to create complex parametric geometry.

In this paper, we employed digital simulation tools for quantitative daylighting expressed by the UDI. We combined them in a MOP with radiation analysis for PET to identify an optimum canopy design.

Since this is ongoing research, the paper also presented a brief literature review on all topics uncovered through the study. We discussed energy consumption and performance, computational simulations, parametric simulation, SBO, and evolutionary algorithms. We also introduced notions of transient conditions and transitional spaces.

The primary purpose of this study was to simulate and optimize a complex parametric geometry based on Origami shapes, applied in a semi-outdoor space where neither indoor nor outdoor assessment indices would apply.

Among the main conclusions, we can highlight that the optimization objectives were conflicting. The higher the PET values, the lower the UDI, due to the infrared heat transfer. The higher the illuminance levels permitted, the higher the infrared energy and, therefore, the radiation levels.

Optimization results returned a Pareto Frontier that illustrates this logic. The optimization process dealt only with quantitative objectives, thus making the designer responsible for applying qualitative objectives. Generally, the Utopia point in a Pareto Frontier shows the best optimization results for both objectives. However, knowing that maximizing daylight would offset PET values from the thermal comfort sensitivity, we chose to analyze the Utopia point and extreme cases.

Another important conclusion concerns the use of the diversify parameters option, not implemented in the cited literature. For all zones, the diversify parameters increased the quality of results in a distinctive way. For Circulation Zones, it was necessary to configure a MOP. It sped the parameter convergence and provided more optimal results. For Entrance and Atria Zones, it also helped to speed the optimization process delivering better results.

In a MOP, there no final optimal result. For the three cases, the three selections can configure an optimal geometry, depending on the objective envisioned. If we are to answer to the optimization objectives set in Octopus, we could say that the results near the Utopia point are the optimal solutions.

Selecting Utopia points, for Circulation Zones, the maximization of PET reached 93.75% of simulated hours in thermal comfort. Since PET was the only optimization objective inserted in Octopus for this condition, each 93.75% point in the graph represents a different geometry, which gives the designer the option to choose between slightly different canopy configurations.

For the Entrance Zone Utopia point, PET was 85.1%, and UDI was 62.5%, which means that in 85.1% of the simulated time, the user is in thermal comfort and 62.5% of the time, the illuminance levels in the simulated space are between 100 and 2000 lx. In the analysis of the Pareto Front for the second condition, the maximum PET is 90.7%, and the maximum UDI, 93.8%. PET is lower in the second condition due to the context geometry that affects radiation levels in the canopy.

For the Atria Zone, the results were similar to the second condition, although PET was consistently higher, with a lower maximum. For the Utopia point, PET was 82.7%, and UDI, 62.5%, which means that despite the decreased radiation levels, illuminance levels were maintained. This condition may have resulted from reflected radiation inlet, which reduces infrared radiation and internal heat gains. For this zone, the maximum UDI was 93.8%, and the maximum PET was 86.1%. Once more, PET is lower than the previous condition, due to additional context geometry that acts as shading.

Comparing these results with the literature review, Cartana (CARTANA, 2018) achieved maximum results of 89.34% UDI when applying a shading façade. In his simulation, he considered an office room with 60 analysis points and managed to keep most of the results close to 85.0% UDI. Since it was an indoor space, his work does not address PET use.

The research as a whole strives to investigate the following question: How is the process of designing a performance-based canopy created by simulation-based optimization?

To achieve this purpose, we investigated the performance-based design process for a canopy, using parameterization, computational simulation and optimization techniques to establish all the design steps.

Heretofore, we found out that the simulation and optimization tools, although not yet ingrained among designers, and despite some limitations, proved their potential for integration within the design process and specific areas in architecture and engineering, such as performance analysis.

The simulations were performed for Viçosa, MG, Brazil (Latitude 20º 45 '14 "S, Longitude 42º 52' 55" W, Altitude 648m), but the whole research strives to create a straightforward parametric design methodology that designers can reproduce anywhere.

4.5.1 Research Limitations

Regarding the optimization processes through evolutionary algorithms, we highlight the limitation of computational processing for complex geometries. Honeybee and Ladybug operate very well when using relatively simple geometry generated in the Rhino+Grasshopper suite. However, if the geometry is a complex analysis file, Honeybee takes considerable computational time. In these cases, DIVA works faster alone. This obstacle results from Honeybee operation with breps, which is an abbreviation for boundary representation. Breps are a method for representing solid shapes with a collection of connected surfaces, which potentially provides a cleaner workflow in Honeybee, allowing the designer to manipulate the geometry while the simulation process is in operation.

If the input geometry in Honeybee is a mesh, which is a surface composed by a collection of triangles or quadrilaterals, the user needs to convert it into a brep for the simulation to work, which can take a long time.

Concerning the canopy implementation, we simulated the geometries with only one immediate context geometry due to the amount of computational time required for daylight SBOs.

Lastly, due to the great demand for computational processing to generate masks for models composed by meshes, the masks could not be created.

4.5.1 Future Research Ideas

Since this is ongoing research, we plan to validate our optimization process by using prototypes and exploring digital manufacturing strategies. We also strive to create larger-scale models, aiming to answer to materialization, connections, and modeling challenges.

Since canopies are important for Brazilian climate, we also intend to further analyze the likelihood of glare through the use of solar control elements.

We also strive to implement all the Ladybug tools for Grasshopper when inserting Computational Fluid Dynamics' (CFD) analysis in the research.

Since the initial radiation and daylight simulations presented only immediate context geometry, we aspire to conduct studies on solar control elements developed in consolidated urban situations, aiming to evaluate the effect of the surroundings, while enabling further variation in the canopy parameters.

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5 CHAPTER 5 – CONCLUSIONS

5.1 Conclusions

This thesis is an investigation of the design process of a modular canopy, produced with the aid of parametric modeling tools and simulation-based optimization (SBO) for solar radiation admission and natural light distribution.

As elements of innovation, the proposed topic combines sustainability issues in the built environment with digital technologies for building design and production. The research methodology employed during the design process concerned the application of the Rhino+Grasshopper suite. We explored its analysis and representation tools to present results graphically, which facilitates the visualization and interpretation of thermal or luminous comfort analysis.

As one of the main conclusions, it is essential to perceive that the base cases, are situations with excess radiation admission and heterogeneous light distribution.

The solar control elements reduced the excess admission of solar radiation and natural light, making the distribution of natural light more homogeneous, in addition to reducing the likelihood of visual discomfort due to glare.

The gradual accretion in the geometric complexity of the solar control elements proved that the performance results could be generalized from the parametric behavior of simpler geometries, such as the leaf-inspired models, to models with more elaborate shapes, such as the Origami explorations.

As for the design and investigation of complex geometries, we can highlight the importance of parametric modeling and digital fabrication tools employed. Without these tools, the representation, materialization, and analysis of the canopy would be impracticable. We can also observe that the widespread incorporation of these tools, along with the exploration of their formal and tectonic possibilities by the academic community and architects may bring significant changes to the design process of future architectural production.

The results of the optimization processes through the use of genetic algorithms were consistent in terms of cause and effect relationships between the parametric variations and the performance of the optimized elements. Nonetheless, we can register limitations on this process. There are considerable time and complexity involved in the elaboration of the parametric script and optimization set, considering the evaluation of every parametric shape possible.

Through this research, we can also recommend that, despite all the variability of models, the best solution should consider qualitative evaluations and vary for each project situation. Architects should consider constraints such as building use, visual relations, architectural composition, and architecture identity.

Concerning specific conclusions, in Chapter 2, the use of a solar control element diminished the excess of direct beam radiation admission, keeping diffuse radiation high and constant. The beam portion of radiation diminished up to 94.5% for the best-case scenario when compared to the annual average, maintaining diffuse radiation close to the weather file average values. The study served as a methodology test and modeling star. We could understand the plugins, especially when regarding reflected radiation, since the awning shifted its lower damper, creating an upper flap to prevent direct beam radiation admission while maximizing the percentage of reflected radiation.

As the leading cause/consequence between geometry parameter variations and elements' performance, we observed the importance of the combination of parameters related to length Y and aperture Z in the upper damper and length Y in the bottom damper.

Throughout this chapter, we chose to work with radiation analysis due to time restrictions. As radiation analysis is often more straightforward, the optimization process is less time and cost-consuming, and we could scrutinize the results within days. The use of radiation analysis was so crucial for this research that we adopted in Chapter 3 and 4 in order to implement different methodology procedures.

A critical methodology procedure used in the chapter is the adoption of the ABC curve. The results presented as Pareto solutions in the ABC curve indicated the importance of the designer's decision, primarily in the choice of the final solution, since the curve and the selection of data have to be made by the researcher.

We used ABC analysis as a means to identify more critical solutions. The ABC curve also provided a mechanism for identifying all the different importance categories, suggesting that not all solutions are of equal importance.

In this configuration, 'A' items were essential, contributing heavily to beam radiation diminish without reducing diffuse radiation. It is a smaller category but comprises the best results.

'B' items were valuable, but of course, less important than 'A' items and more important than the marginally significant 'C' items. Therefore, 'B' and 'C' categories were not appraised.

In Chapter 3, one of the main conclusions is regarding the use of Factorial Analysis. The selection of the most robust factors ensured less computational time and helped to define the parameters that would generate more optimal shapes.

During this chapter, we prefaced accessible digital simulation platforms, along with quantitative radiation analysis and qualitative radiation visualization, to discover the level of significance of factors acting on the canopy shape.

The primary purpose of this article was to create a complex parametric geometry based on Origami shapes and analyze some of the main factors with a potential contribution to the incidence and transmission of Solar Radiation in the Canopy, using Factorial Analysis. The design process was restrained as we chose to work with one specific shape. However, the application of the Analysis of Variance (ANOVA) as a methodology procedure is interesting in the performance-based design scenario.

We implemented the ANOVA to examine the differences among group means in a sample process. The approximation of the ANOVA experiment was straightforward. We applied a fixed-effects model to the factors to see whether the response variable values change, which enabled the estimation of the ranges of the response variables.

As we included observations at all combinations of levels of each factor, we had a factorial. Factorial experiments proved to be more efficient than a series of single-factor experiments, as we tested various implementations using various possibilities of replicas. We also concluded that the model efficiency grown as the number of factors increased.

Notwithstanding, the use of ANOVA to study the effects of multiple factors has a complication. In a 3-way ANOVA with factors x, y, and z, the model includes factors for the main effects (x, y, z) and factors for interactions (xy, xz, yz, xyz). All terms require hypothesis tests. The proliferation of interaction factors increases the risk that some hypothesis tests will produce a false positive by chance.

Fortunately, experience says that high order interactions are rare, and the ability to detect interactions is a significant advantage of multiple factor ANOVA. Testing one factor at a time hides interactions, but produces inconsistent experimental results.

Besides, the simulation for radiation of the 5°, 15° and 20° inclination that was applied after the factorial proved that the slope differentiation impacts the design, on the amount of radiation received by the surface and on the user comfort level as the factorial suggested.

In these simulations, a considerable part of the percentage of time in discomfort (which were 32.3% of time) is related to cold hours mostly reported during the nighttime and before 6 AM, mainly during winter and fall. The discomfort happened mainly between May and August (relative to fall and winter, respectively). Adopting adiabatic walls for the simulated model eliminated internal heat flows between zones, which caused the night times to seem colder than they were. We intended to unselect night hours on Ladybug®, but the plugin has a limitation concerning time selection. Since it did not allow us to select a specific time-span we ran whole day and year analysis and decided not to omit the results from the hours with no radiation acceptability. We assumed that the discomfort happened out of the simulation hours of interest.

In Chapter 4, we also investigated optimization objectives. Among the main conclusions, we can highlight that the use of the Diversify Parameters option as a new optimization objective created more individuals, better results, and spent less computational time.

We did not insert the Diversify Parameters option during the methodology test in Chapter 2, as we had two well-defined objectives. Even though we had better results with the Diversify option, the SBO delivered more mutated individuals to the optimized field without changing the basic configurations (Elitism: 0.5; Mutation Probability: 0.1; Mutation Rate: 0.5; Crossover Rate: 0.8) and generated more extreme cases, which we rejected.

Concerning the genetic algorithms used, in Chapter 2, the application of SPEA-2 returned reliable results since it was a bi-objective optimization. In Chapter 4, we chose to work with HypE, which is more suitable when dealing with more than two objectives. In this case, we had bi-objective optimizations and a Diversify Parameters option, creating a multi-objective optimization.

The optimization algorithm selection happened because we performed a methodology test in Chapter 2, in which the literature review suggested that HypE would perform better for multi-objective optimizations that we would implement later.

The SBO results were coherent as to the cause and effect relations between the parametric variations and the optimized element, but the parametric modeling lacked some shape parameters. As we decided to test only the factors that the factorial defined as robust, we did not employ some important parameters that would contribute to a better geometry. We could have considered module angulation, size limitations for modulation, multiplications, self-supporting situations, and maintained the Honeybee® simulation zone as a fixed variable.

The first approximations to Transitional spaces required a selection of comfort indexes that could work for both indoors and outdoors. The use of Physiological Equivalent Temperature (PET) for predominantly outside spaces and Useful Daylight Illuminance (UDI) for indoors worked, and we were supported by a literature review.

Striving to establish a design process after the research, we can appoint that the methodology test applied in Chapter 2 was necessary for the whole process as it anticipated issues that could occur during the main topics of the research.

Testing the methodology allowed us to see that the definition of objectives and parameters for the SBO were imperative for a better simulation process as well as for saving computational time.

We acknowledge that the performance-driven design is based on interoperability and can occur in various stages of design, planning, and construction. We also acknowledge that all the stages could be simultaneous. For the sake of defining which part of the methodology worked, we are listing the steps as they appear.

In the second chapter, the definition of the script for shape parameterization and optimization was the first step in which the geometry was defined, and limitations are set. The simulation zone is also established during this step. All parameters are specified for the optimization, and depending on the number of parameters, we can define the optimization problem as a mono, bi, or multi-criterion problem.

Concerning the selection of optimization objectives, we did not establish a methodology during Chapter 2. We perceived the necessity to rationally select better objectives, since the more objectives, the more computational time. For this reason, in Chapter 3, we applied the factorial as a means of defining the most significant factors in order to save simulation time. This step helps reducing time when the simulation demands a substantial computational time. When manipulating less demanding simulations, this step is an overcompensation.

When managing the optimization, according to the results of this thesis, genetic algorithms provided by Octopus were a rational choice. We did not implement any other evolutionary algorithm that was not already embedded in the optimization motor.

For mono and bi-criterion problems, SPEA-2 performed well. For multi-objective design problems, we should select HypE.

The ABC curve also helped to visualize the best results, diminishing the number of solutions as we selected only the best fit. This analysis was also crucial during Chapter 4 and was only implemented because we tested it beforehand.

For radiation and daylight analysis, Ladybug® and Honeybee® were a good selection since Ladybug® provided fast radiation feedback, and Honeybee® allowed us to work with Radiance®, Daysim®, and EnergyPlus™, which are extensively validated simulation tools.

Concerning the selection of the best results, we can conclude that, in general, the three last generations compose the majority of the Pareto frontier, which is also indicative of conversion. In multi-criterion optimization problems, all points on the Pareto front are potentially an optimal solution.

Since we did not apply a qualitative analysis for the results, we defined the Utopia point as an ideal standard for quantitative selection since it has coordinates that simultaneously maximize both criteria, occupying the edge of the criterion space in the Pareto frontier knee.

Another possibility for selecting the best results rely on qualitative analysis. In this case, the researcher should consider which objective has a more significant impact on the determination of the best solution.

5.2 Research Limitations

Regarding the parametric modeling, due to time constraints, we defined a geometry through the literature review. We developed its parametric script for the simulation-based optimization (SBO), which caused a simplification of the parameters for the optimization. The parameters should be broadly reviewed before the optimization process.

We also restricted some analysis, regarding materials, constructability, and module sizing, for instance, in an urge to examine various methodologies for the performance-based design. Since the focus of the research leaned towards performance analysis and less anent geometry, the shape worked as a catalyst for the simulation, and we applied only a few qualitative analysis.

Regarding the optimization processes through the use of evolutionary algorithms, we highlight the limitation of computational processing when operating with complex geometries even before the factorial analysis and selection of most signifying parameters.

Due to time and cost-consuming daylight SBOs, especially when working with Honeybee®, the canopy geometries were analyzed only in the immediate context, which decreases the influence of the surrounding impact, which is not practical.

Lastly, among the main limitations of the research, we can highlight that there is a high demand for computational processing to generate masks for models composed by meshes using the Ladybug® plugin. For this reason, we did not include them in this dissertation. We should also stress that working with complex geometries in Ladybug® and Honeybee® can lead to inaccuracies in the result interpretation.

5.3 Suggestions for Future Researches

To conduct studies of solar control elements developed in consolidated urban situations aiming to evaluate the influence of the surroundings and, at the same time, permitting more variation of the dimensions for the modules as well as the canopy.

To explore digital production strategies and materials for small prototypes and larger-scale models aiming at validating this study and producing higher precision evaluations and measurements related to the performance of solar control elements with complex shapes.

To discuss matters of materialization, execution, and construction, acknowledging design problems when working with small prototypes.

To analyze qualitative variables regarding the social role, architectural interest, best materials, good visual performance.

To develop and evaluate new parametric variations, based on the current architectural production, aiming to improve their capacity for selective admission of solar radiation, together with the sufficiency in the admission of natural light and reduction of visual discomfort due to glare. We also suggest more in-depth studies on the behavior of complex forms, regarding the ability to reduce the likelihood of glare due to reflections on multiple surfaces.

APPENDIX A

Factorial Analysis And Analysis Of Variance (ANOVA)

According to Hair et al. (2005), among the various Sensitivity Analysis, the Factorial Analysis is the only one that allows the investigation of all possible variable compounds, enabling to understand the interrelationships between a large number of factors.

According to Montgomery, Runger, and Hubele (2012), there are no restrictions regarding the number of factors and levels that a factorial design can contain. The Factorial Analysis outputs an Analysis of Variance (ANOVA), which permits the evaluation of the confidence level of the model, meaning an F-value significantly different from zero.

The ANOVA is a compound of statistical models used to identify which factors, variables, or combinations are the most prominent in a simulation. It also assesses the effect caused by each factor and its significance for the entire model, comparing the mean of several groups of elements at the same time.

The ANOVA separates the total variance into several parts, linked to definite sources of modifications, to test every hypothesis on the combination of factors. It statistically identifies robust simulations, probing the output variables and the various inserted factors.

It uses F-statistics calculated for all the parameters as a means for comparison to their critical F-value. The F-value determines if whether the model is associated with the variance response or if its missing higher-order terms. Summarily, a sufficiently large F-value indicates that either the factors or the model are significant.

The F-value depends on the total degrees of freedom (DF).

Total DF is the amount of information in each implanted data. Minitab uses that information to circumscribe the values of unknown population parameters and automatically generates the Total DF. Therefore, increasing the number of factors provides more information on the population, which increases the total DF. That is the main reason why the first ANOVA has 39 DF, and the second has 79 (Table 01 and 02).

Minitab uses these Total DF values as a numerator and denominator to calculate the probability of obtaining an F-value that is at least as extreme as the critical F-value.

Table 01 - Analysis of Variance for the first Factorial Analysis Model in Chapter 03.

Analysis of Variance					
	Source	DF	Contribution	F-value	P-value
Order	Model	3	87,15%	36,44	0,00
1st	Linear	2	79,13%	32,27	0,00
	Cardinal Rotation	1	7,58%	7,84	0,00
	Slope	1	71,55%	56,70	0,00
2nd	2-Way Interactions	1	8,02%	44,78	0,00
	Cardinal Rotation*Slope	1	8,02%	44,78	0,00
	Error	36	12,85%		
	Total	39	100,00%		

Source: The Authors

Table 02 - Analysis of Variance for the second Factorial Analysis Model in Chapter 03

Analysis of Variance					
	Source	DF	Contribution	F-value	P-Value
Order	Model	7	77,63%	35,69	0,00
1st	Linear	3	72,17%	77,42	0,00
	Cardinal Rotation	1	4,32%	13,91	0,00
	Collateral Rotation	1	0,01%	0,03	0,87
	Slope	1	67,84%	218,32	0,00
2nd	2-Way Interactions	3	5,42%	5,82	0,00
	Cardinal Rotation*Collateral Rotation	1	0,01%	0,02	0,90
	Cardinal Rotation* Slope	1	5,38%	0,02	0,00
	Collateral Rotation*Slope	1	0,04%	17,31	0,72
3rd	3-Way Interactions	1	0,03%	0,13	0,75
	Cardinal*Collateral*Slope	1	0,03%	0,10	0,75
	Error	72	22,37%	0,10	
	Total	79	100,00%		

Source: The Authors.

Minitab also uses the F-value to calculate a P-value, which tells the statistical significance of all factors in the model. The P-value measures the evidence against a null hypothesis, which means that lower probabilities, or lower P-values, provide stronger evidence against a null hypothesis.

The significance testing has a null hypothesis (Ho) and an alternative hypothesis (Ha). Both are opposite and mutually exclusive patterns regarding the interrelationship between the factorial inputs. The null hypothesis (Ho) denies the existence of factor associations, while the alternative hypothesis (Ha) establishes that all factors are correlated.

In theory, the P-value is a constant measure of evidence. In practice, it is apportioned into highly, marginally, and not statistically significant with stoppage at $p<0.01$, $p<0.05$, and $p>0.10$. (GELMAN, 2012)

According to Ferreira and Patino (2015), the P-value denotes the probability of observing a significant or more significant difference than the one found under the null hypothesis. However, if the P-values are marginally significant or above the threshold of significance, another factorial may be adequate to investigate its worth.

The ANOVA also contains a source, an error, and a contribution. The source is the variation in the data, and the error is variability within the groups or an unexplained random error.

The contribution displays the percentage that each source adds to the total sequential sums of the square. Higher rates indicate that the source accounts for more of the variation in the response.

Comprehending all the notions behind the ANOVA, we can analyze the results obtained in Table 01 and 02.

In this particular ANOVA, all P-values are 0.00. According to Figueiredo Filho et al. (2013), P-values are never exactly zero, but are usually reported as three digits (as Minitab cannot render very low numerals). Therefore, they are interpreted as less than 0.01.

According to Gelman's classification, this would suggest the results are all highly significant.

Although, a joined assessment of Contribution and P-Value shows that the first-order factor Slope is responsible for a large portion of the model robustness, being the most significant factor in the first Factorial Analysis.

In the second ANOVA, P-values vary from 0.0 to 0.9. Collateral Rotation assumes one of the highest P-values, which means that its insertion did not contribute to the robustness of the model. Any factor related to Collateral Rotation registers not statistically significant P-values.

All other factors, as in the first ANOVA, are highly significant. The Slope factor is responsible for 67.84% of the model contribution, which, combined with the P-value, makes it the most robust element in the ANOVA.

Compiling, any complex analysis requires the identification of target quality attributes that portray its output and the factors related to those attributes.

Comprehending all the factorial outputs, the researcher needs to identify a list of potential factors, the robustness of the relationships between those factors, and the target attributes to be quantified.

That is one reason for using Sensitivity Analyses that are Variance-based. These techniques make it possible to identify sensitive parameters depending on the targeted attributes.

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